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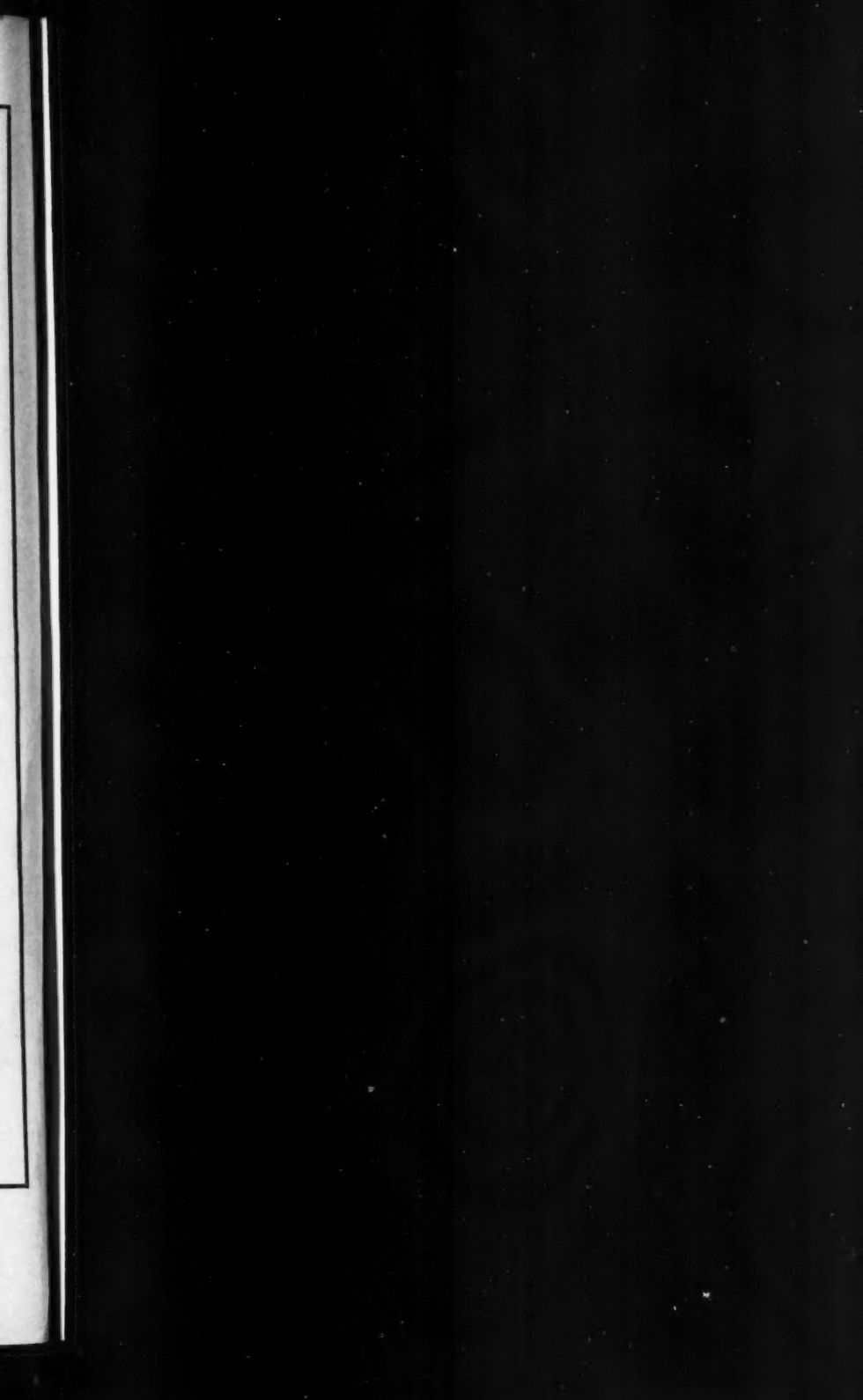

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THE INSTITUTE OF PETROLEUM.

AN Ordinary General Meeting of the Institute of Petroleum was held at Manson House, 26 Portland Place, London, W.1, on Wednesday, May 11, 1949, with the President, Mr E. A. Evans, in the Chair.

The Minutes of the preceding Ordinary General Meeting, held on April 13, 1949, were read, confirmed, and signed.

THE GENERAL SECRETARY (Mr D. A. Hough) announced the names of those elected since the last general meeting.

THE PRESIDENT introduced Dr F. Morton who, before presenting the following paper, said : The work I am to discuss was completed in 1944, as part of a comprehensive survey of the crude oils of Trinidad. In preparing the work for presentation I have not had the opportunity of discussion with my fellow authors, all of whom are some 4000 miles away. For any errors or omissions I am entirely responsible.

THE CRUDE OILS OF TRINIDAD. PART III. RELATIONSHIP OF CRUDE OILS AND STRATIGRAPHY IN THE MORNE DIABLO-QUINAM FIELD.

By K. W. BARR,* FRANK MORTON,† A. R. RICHARDS,‡ and R. O. YOUNG.*

SUMMARY.

The crude oils from the Forest, Upper Cruse, and Middle Cruse sand zones of the Morne Diablo–Quinam field have been examined by methods previously described. The lenticular Forest and Upper Cruse sand zones contain a variety of oils. The sheet sands of the Middle Cruse zone each contain a uniform type of oil which, however, varies from sand to sand. The origin of these oils is discussed, and it is concluded that impregnation of the sands by migration from the Los Bajos Fault is unlikely.

INTRODUCTION.

THE present work forms part of a series of researches undertaken to examine the problems of the origins and possible sources of Trinidad crude oils, in the light of their chemical and physical properties. The geo-chemical studies of D. C. Barton,[1] H. Hlauschek,[2] and more recently

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the work of the Tulsa Geological Research Committee [3] have shown that evidence concerning the chemical nature of crude oils is of value in the study of problems related to the origin, accumulation, and migration of petroleum. The replies to the questionnaire-symposium "The time of origin and accumulation of petroleum" [4] indicate, however, that information on the relationship between crude-oil character and stratigraphy is lacking in many areas. Information from a large number of petroliferous provinces would materially assist the development of many current problems of petroleum geology.

The oilfields of Trinidad offer an excellent opportunity for geochemical studies, since the oils exhibit a wide variation in chemical properties within a limited stratigraphical and geographical range. The oil indications of Trinidad extend from the Cretaceous to the Pliocene, although commercial production is at present limited to the beds of Middle and Lower Miocene and Upper Oligocene age. Possible source beds, however, range from the Middle Miocene to at least the Cretaceous, although, as in most other oil-producing areas of the world, geological evidence is at present insufficient to identify these with certainty.

Earlier papers [5, 6] in this series have described the analysis of a number of crude oils from various producing zones in Trinidad and the use of such analyses in the study of a complicated producing area.[7] In the present paper a detailed study of the oils of the Morne Diablo–Quinam field is described, and the results discussed in relation to the suggestion that the Los Bajos Fault has acted as a major feeder fault. The results are also of interest in relation to the problems of the derivation of oil in discontinuous reservoirs and multiple oil and gas reservoirs.

Relationships between Crude Oil Composition and Stratigraphy.

The crude oils of the world exhibit a wide variation in type.[8] Whilst certain large areas such as the Pennsylvanian area may contain a sensibly uniform type of oil, many areas and individual fields contain several varieties of crude oil. In early studies [9] it was noted that, when several types of oil occurred in a single petroliferous province, the specific gravity of the oils generally decreased with depth. D. C. Barton [1] from an extensive study of the crude oils of the Gulf Coast and from a study of published analyses of other U.S. oils noted that the oils became more paraffinic, lighter in gravity, and contained increasing quantities of light fractions with increasing depth and age (Table I). Similar conclusions were reached by H. Hlauschek [2] from a study of the oils of the Carpathian area correlated with an exhaustive study of published analyses of crude oils throughout the world. Hlauschek summarized his findings in two rules, which agree well with the findings of Barton.

Depth Rule. With oils of different composition or gravity in the same petroliferous province the heavier oils (generally more naphthenic) tend to occur above the lighter (more paraffinic) oils.

Age Rule. Oils occurring in Paleozoic formations are nearly always of a paraffinic type, while Tertiary oils are commonly naphthenic or intermediate-base type.

Hlauschek gave ample evidence in support of the general application of his two rules, but he also cited several exceptions in which lighter oils had been found at both stratigraphically and structurally shallower depth than heavy oils. R. O. Young [10] has called such exceptions "oils of

TABLE I.
(Barton.)

Region.	Age of oil horizon.	Gradient, ° A.P.I. per 1000 ft.
California	Cretaceous and Tertiary	5·8
Colorado	Upper Cretaceous	5·2
,,	Lower Cretaceous	2·3
,,	Jurassic	6·0
,,	Carboniferous	Positive gradient
Oklahoma	Permian	4·8
,,	Pennsylvanian	2·2
,,	Ordovician	0·0
Texas	Mio-Oligocene	2·3 to 2·5
,,	Eocene	Slightly higher
,,	Woodbine Cretaceous	3·0
,,	Lower Cretaceous	3·5
West Texas	Permian	3·8
,,	Cisco	3·8
,,	Bend	7·2
Venezuela	Tertiary	7·5

TABLE II.
Distribution of Gravity of Oil with Depth at Balakhany.
(After Gurwitsch.)

Depth, m.	Specific gravity.	Gradient increase, m.
190	0·7817	
		0·0000566
296	0·7873	
		0·0001609
360	0·7976	
		0·0002118
394	0·8048	
		0·0002682
526	0·8402	
		0·0002837
580	0·8555	
		0·0003150
600	0·8618	

abnormal distribution" in contrast with the "oils of normal distribution" which follow Hlauschek's first rule. The generalization that paraffinic oils are deeper and older than naphthenic oils seems to apply even for oils of abnormal distribution. Such abnormal distribution has been reported by Gurwitsch [11] at Balakhany (Table II); D. A. Grieg [12] at

Salsamaggoire (Table III); J. Taff [13] at Kettleman Hills (Table IV); in Burma (W. J. Wilson [14]); Roumania (Krejci-Graf [15] and Hlauschek [2]); Japan (W. Emmons [16]); and in Trinidad (E. H. Cunningham Craig,[17] G. H. Scott,[18] and C. C. Wilson [19]).

TABLE III.

Distribution of Gravity of Oil with Depth at Salsamaggoire.

(After D. A. Greig.)

Well.	Depth, m.	Sp. gr. of crude.	Gasoline, % below 150° C.	Kerosine, % 150°–300° C.	Residue, % above 300° C.
11	158–173	0·7933	55	35	15
54	198–215	0·8115	45	44	11
203	399	0·8181	36	42	22
203	503	0·8230	33	44	23
60	684	0·8356	0	80	20
60	1035	0·8493	1	74	25

TABLE IV.

Oil Distribution at Kettleman Hills.

(J. Taff.)

Well.	Depth, ft.	Depth of penetration of Temblor Sands, ft.	Crude oil.	
			° A.P.I.	Sp. gr.
1	6776	776	68·3	0·7082
2	7133	900	67·8	0·7100
3	7037	915	61·4	0·7335
4	7073	958	61·3	0·7377
5	7176	1005	58·6	0·7443
6	8026	1119	55·5	0·7567
7	7952	1118	42·0	0·8156
8	7786	1217	42·0	0·8156
9	8091	1131	36·9	0·8403
10	7879	1172	37·0	0·8398
11	8234	1277	35·0	0·8498
12	8338	1301	35·0	0·8498
13	8601	1378	35·0	0·8498
14	8328	1392	36·5	0·8423
15	8789	1405	35·1	0·8493
16	8997	1432	35·7	0·8463
17	8858	1450	34·2	0·8540

Several explanations have been advanced to account for these types of oil distribution. These may be divided for ease of discussion into "Primary" and "Secondary" causes affecting oil distribution. The use of these terms is analogous to that adopted by V. C. Illing [20] to cover the stages in the formation and migration of oil, namely,

(a) *Primary*—due to source material and conditions of formation.

(b) *Secondary*—due to the conditions to which the oil has been subjected since its formation.

Primary Factors Influencing the Character of a Crude Oil.

Source Beds.

The environment and the conditions of the formation of petroleum are still a subject of controversy, and at present two opposed schools of thought exist. Krejci-Graf first advanced the view that petroleum was formed from richly organic source beds—the Black Sea (Euxenic) type of environment is usually considered to yield beds of this type, which are also termed sapropelitic. Temperatures and pressures compatible with a minimum depth of burial of 4000 m were considered to be necessary, under which conditions the organic material was converted into a "proto-petroleum," paraffinic in character and comparatively rich in light products. The heavier naphthenic oils and asphalts were believed to be alteration and oxidation products. W. Seyer [21] and C. W. Washburne [22] have supported this view, but G. H. Schultze [23] considered it to be thermodynamically unsound.

The opposing theory that oil may be formed from sediments of only moderate organic content and without the necessity of great depth of burial has evolved gradually. The theory is described by V. C. Illing.[24] The concept that compaction currents enable the oil to escape from the clayey source beds into the reservoir beds demands a rather shallow depth of burial and early formation of the oil. The lack of the necessity for a highly organic content in source beds is supported by the rarity of beds rich in organic matter in both ancient and recent marine sediments (P. D. Trask [25]).

The view that proto-petroleum was heavy, asphaltic, and naphthenic was advanced by H. Höfer in 1923 [26] and was based on the belief that asphalts were original and not oxidation products. This view is strongly supported by A. Triebs [27] and B. T. Brooks,[28] who cite the preservation of porphyrins in the crude oils as evidence for low-temperature formation of oil and for the original nature of the asphaltic material. E. Berl [29] supports the view that proto-petroleum is naphthenic, but considers that oil formation is deferred until the depth of burial is sufficiently great to permit cracking and hydrogenation processes to take place.

The view that the shallow, low temperature origin of oil is generally accepted forms one of the conclusions of the editors of the questionnaire-symposium "The time of origin and accumulation of petroleum." [4] They also conclude that evidence favours the possibility that clays and marls with but a low organic content may have been sources of oil.

Source Materials.

No definite relationship between the nature of crude oils and their source materials has yet been proved. This is partly due to the uncertainty concerning source beds and partly due to the fact that crude oils may have undergone considerable alteration since their formation. Nevertheless, many interesting contributions have been made. J. E. Hackford [30] suggested that the heavy naphthenic Mexican crude oils were formed from algæ because of the relatively high nickel content of the crude-oil ashes. Vanadium is also present in the Mexican ash. Subsequent

investigations by E. Longobardi [31] indicated that, while nickel is present in nearly all crude oils, vanadium is present in asphaltic oils. A. P. Vinogradov and C. C. Bergmann [32] found that the vanadium content was proportional to the asphalt content, and they pointed out that the ascidians, in particular, are rich in vanadium and flourish in the bottom sea mud.

From studies of Californian oils, J. Taff [13] has suggested that foraminiferal shales yield naphthenic oils containing wax, but with little asphalt, while diatomaceous shales yield naphthenic oils with asphalt, but little or no wax. Both series of oils occur in beds of Upper Tertiary age. D. B. Reger [33] found that oils occurring in the Appalachian limestones are heavy and asphaltic, while the oils found in sands in the area are light and paraffinic. The differences may be due to higher proportions of vegetable matter in the source beds from which the sand oils were derived. E. Berl [34] has suggested that the pH value of the source environment may influence the nature of the ultimate hydrocarbon products. This theory is analogous to that concerning the formation of different types of coal, in which source environment is now believed to have played a very important role. Some such factor must be postulated if the theory that oils occurring in lenticular—shoe-string formations are indigenous to the sand or to the enclosing shale, is to be accepted in view of the variations in crude-oil types occurring in adjacent sand lenses in the same shale formation.

H. Hlauschek [2] suggested that differences in source material could account for his two rules of oil distribution. Since the lower forms of plant life are deficient in lignin, Hlauschek argued that Paleozoic plants would likewise be deficient in lignin. He believed that lignins would tend to form cyclic compounds, which should therefore be lacking in the older oils—and these oils had already been observed to be generally paraffinic. Alternatively, Hlauschek suggested that climatic conditions would affect the source material and account for the crude-oil variations, since low temperatures encourage the building up of unsaturated fats by organisms and these unsaturated compounds could yield cyclic compounds. This would provide an explanation of the variation in Gulf Coast crudes observed by D. C. Barton,[1] since the Gulf Coast climate became progressively colder in Tertiary times. Hlauschek also stressed the two types of source material available in deltaic sedimentation, namely marine and terrigenous material. The latter consists mainly of lignins and humins, which Hlauschek considered should tend to form cyclic compounds, while the marine material should form open-chain compounds. Berl,[34] on the other hand, considered that lignins are converted only to lignites and that oils and bituminous coals are formed mostly from the carbohydrate content of plant materials.

Although little has been definitely proved, it is reasonable to assume that source material and environment have been largely responsible for differences in crude-oil character. A discussion on the mechanism by which the source material is converted into petroleum is beyond the scope of this paper.

Secondary Factors Influencing the Character of a Crude Oil.

These factors include all those which may have modified the character of an oil after it has been formed. It will be realized that, if the "shallow-depth" theory of the origin of oil is accepted, the occurrence of different types of oil at various depths can be explained by assuming each oil to be indigenous to the horizon in which it is found—or at least to the underlying horizon. In this case it is unnecessary to postulate secondary alteration of the oil. On the other hand, the "deep burial" theory of the origin of oil requires that the character of the oil changes from a paraffinic proto-petroleum to the naphthenic-asphaltic type oils found at shallower depths. Hlauschek has pointed out that "the conversion of paraffin hydrocarbons into naphthene hydrocarbons is an essential constituent of this theory and may not be withdrawn without bringing the whole theory into ruins." The conversion of paraffins into naphthenes is suggested to have occurred by the effects of pressure and temperatures existing at depths in excess of 4000 m, and by adsorption, or filtration, during trans-formational migration. Chemical and biochemical processes have also been suggested as possible causes of the occurrence of naphthenic oils above paraffinic oils.

Chemical Alterations of Oils.

The possibility that some oils of Northern California had been altered by oxidation was recognized by C. S. Rogers,[35] who found that the specific gravities of many of the oils of the Midway–Sunset and Coalinga fields varied directly with the sulphur contents of the oils. It had previously been considered that the heavy oils, commonly occurring at shallow depths, had been derived from lighter oils by loss of light fractions. Rogers suggested that the "heaviness" of the oils was due to polymerization or oxidation, possibly due to reactions between the oils and oilfield waters. The suggestion was supported by Höfer's observations that oilfield waters were generally rich in carbonates but poor in chlorides and sulphates. Höfer [36] considered that the sulphates had been decomposed by the action of methane in the following manner:

$$CaSO_4 + CH_4 = CaS + CO_2 + 2H_2O = CaCO_3 + H_2S + H_2O$$

The hydrogen sulphide formed would then be available for the oxidation of crude oils. The feasibility of this reaction has been warmly contested by chemists, but evidence in support of it has been advanced by many geologists—notably E. L. Estabrook [37] in Wyoming, J. C. Smith [38] in Venezuela, and J. S. Parker and C. A. P. Southwell [39] in Trinidad. R. L. Ginter [40] has discussed the possibility of the reaction being the result of biochemical influences.

Numerous investigations of the oxidation of crude oils have been reported. S. S. Taylor and H. M. Smith [41] investigated the oxidation of various types of crude oils in the laboratory and found that although the specific gravity of the distillate fractions was unaltered the residues became increasingly asphaltic. Tests on crude oils produced from an oilfield before and after an air-repressuring project had been applied gave similar results (T. W. Johnson and S. S. Taylor [42]).

The polymerization and oxidation reactions proposed by Rogers are opposed to current opinion that asphalts are not products of oxidation, and further experimental work on this subject is desirable.

Several theories have been advanced which attempt to show that crude oils may alter during geological time under the influence of heat and pressure. D. White [43] compared the geological occurrence of coal and oil and noted that the higher carbon-ratio coals were associated with " lighter " oils and that when the ratio exceeded a certain value wet gas was found in place of oil. The higher carbon-ratios were taken to be a measure of regional metamorphism. Although the theory applied to the Appalachian region, it did not apply so well to other areas and is not accepted in its entirety to-day (W. T. Thom [44]).

Barton considered the variation in the oils of the Gulf Coast to be due to reactions involving heat and pressure over a long period of time, and believed that the time factor might permit such reactions as cracking, hydrogenation, and " methanation " to occur at relatively low temperatures. The absence of unsaturated compounds in crude oils is generally believed to eliminate cracking as a method of oil alteration, whilst the absence of hydrogen in oilfield gases is similarly considered to preclude hydrogenation. Methane in the presence of such catalysts as vanadium and nickel compounds has been suggested as an alternative to hydrogen (H. D. Wilde [45]), but the theory has not met with widespread acceptance. The evidence concerning the hydrogenation theories is reviewed by W. E. Pratt.[46]

Biochemical Alteration of Oils.

Various workers have suggested that bacteria may alter oils by the selective assimilation of specific types of hydrocarbons. The work of Bastin and Greer,[47] and Gahl and Anderson,[48] seems to justify the assumption that bacteria are capable of surviving deep burial. Tausz [49] has reported the isolation of certain bacteria from soils associated with oilfields. These bacteria were all capable of assimilating low-molecular-weight paraffins, but could not assimilate higher paraffins or naphthenes. A. W. McCoy and W. R. Keyte [50] have described the decomposition of oils both by special bacterial cultures and by oilfield brines which contained bacteria. The production of hydrocarbons by bacterial decomposition of organic matter has been demonstrated by Janowski and Zobells,[51] under conditions similar to those existing in marine sedimentation. Further experimental work on this subject will be of considerable interest.

Radioactivity and the Alteration of Crude Oils.

S. C. Lind [52] has shown that simpler gaseous hydrocarbons may be transformed into more complex hydrocarbons under the bombardment of alpha particles, and suggests that petroleum may have been formed from methane in this way. The proposed sources of energy are not confined to the strongly radioactive elements, but such feebly active elements as potassium, which has a wide distribution, are included. Recently developed radioactivity well-logging methods demonstrate the general presence of radioactivity in sediments. B. T. Brooks,[28] in opposing the

general theory, pointed out that free hydrogen, which has been observed as a product of radioactive bombardment of hydrocarbons, cannot be detected in most natural gases. Lind, however, suggests that the hydrogen formed may have taken part in hydrogenation processes. Sheppard has suggested that whilst the formation of petroleum from methane is extremely doubtful it is much more probable that transformation of solid or liquid organic matter occurs in the source beds and that further alteration may occur in the reservoir rocks. E. N. Tiratsoo [53] has discussed the evidence for radioactive formation of oil, and the subject has been reviewed by G. D. Hobson.[54]

Physical Alteration of Oils.

Many workers [55] have investigated the effect of passing crude oils over fuller's earth, silica, clay, and sands. The absorptive earths remove asphalts, sulphur compounds, and aromatic hydrocarbons in preference to the non-polar naphthenes and paraffins. Consequently, it has been assumed that similar processes would occur during the migration of oils across formations having similar absorptive powers. It is unlikely, however, that such conditions are realized in nature, where the clays available are water-wet. W. T. Mendell [56] carried out experiments with both dry and water-wet clays. Colloidal clays were found to lose most of their potency as absorptive agents when water-wet, but other minerals, such as kaolin, which under dry conditions were poor absorptive agents, still retained some efficiency when water-wet. P. C. Nutting [57] has made a study of the absorption of crude oils by silica and certain quartz sands and has correlated this with a study of certain producing sands. He concluded that the effects observed were insufficient to explain the changes in crude-oil character required. G. H. Scott,[18] on the other hand, considers that the variation in character of the Forest (shallow) and Cruse Sand (deeper) oils in Trinidad is due to differences in thickness of the intermediate clay across which he believes the oils have migrated.

Although the experimental evidence suggests that variations in physical properties can be obtained by the action of absorptive agents, there is no evidence to support the view that changes in chemical composition—such as the conversion of paraffins to naphthenes—can be brought about by this means.

Physical filtration does not appear to have been studied to any large extent. V. C. Illing [58] referring to the occurrences of ozokerite in the shattered-clay zones of Boryslaw, and to the solid asphalt veins associated with the migration of asphaltic crude oils, regards them as examples of physical filtration rather than absorption. Such an effect would account for the "abnormal" occurrence of lighter oils at shallower depths than heavier oils. A combination of physical filtration and absorption might be possible.

General Conclusions.

Although secondary factors may have influenced the character of certain crude oils, the primary factors—source material and environment—are now considered to be the major causes of variation in crude-oil compositions. Parker and Van Tuyl summarize current opinion as follows :

(a) *Derivation of Oil in Discontinuous Reservoirs.* "Oil accumulations in discontinuous reservoirs . . . are best explained on the assumption that the source material was deposited (1) in the reservoirs themselves, (2) in the enclosing shales, or (3) in both."

(b) *Multiple Oil and Gas Horizons.* "It is difficult to escape the conclusion that there has been intercommunication between the oil zones of certain oilfields in which there is a close similarity in properties of the oils of several horizons. This is especially true where fracturing or faulting is known to have occurred. However, the contention that in such areas the oil is all from one source does not appear to be justified.

Contrariwise, the acceptance of the view that oils of unlike properties in several productive horizons of the same field are of separate origin is usually favoured, but this interpretation cannot be adopted as a premise until more is learned experimentally and otherwise: (1) concerning the effect of ground water . . .; (2) the influence of various kinds of sediments . . .; (3) the changes that take place in oils as a result of variations in heat and pressure accompanying differences in depth of burial; and (4) the influence of geologic age upon the grade of oil."

Crude Oils adjacent to the Los Bajos Fault, Trinidad.

General accounts of the geology of Trinidad have been given by H. G. Kugler,[59] E. Lehner,[60] R. A. Liddle,[61] and G. A. Waring,[62] whilst a concise summary has been given by H. G. Kugler and V. C. Illing.[63] The location of the principal commercial oilfields of the island is shown in Fig. 1.

The most important petroliferous province in Trinidad is the southern basin, the main structural lines of which are indicated in Fig. 1. The region is cut by the Los Bajos Fault, which C. C. Wilson [64] has described as a longitudinal slip fault, along which the northern block has moved eastwards with relation to the southern block. Wilson considers that horizontal movements of up to 7 miles have taken place along the fault and that the movement which seems to decrease with depth originated in colloidal clays and marls of Oligocene and older age. The fault cuts and displaces structures occurring in Miocene beds and thus was later than the main structural movements. Several important fields lie immediately to the north of the fault, and the Morne Diablo–Quinam field, in particular, is bounded on the south by the fault.

Morne Diablo-Quinam Fields.

The field lies on the northward dipping flank of the Southern Range uplift which, in this area, is cut obliquely by the Los Bajos Fault (Fig. 1). Here the younger Miocene beds with their included sand zones are brought against the shales and marls of the Lower Cruse and Oligocene series, thus affording a clear example of a fault trap. Related to the Los Bajos Fault are a number of subsidiary faults (Fig. 2) which approximate to the dip direction and which cut the flank up into a number of fault blocks. The most important of these faults is the "Well 6" fault which is clearly

defined by surface and sub-surface evidence and by fluid distribution in the Middle Cruse sand zone.

The producing zones are included in the Forest and underlying Cruse formations and fall into three main zones, namely, the Forest Sands, Upper Cruse Sands, and Middle Cruse Sands (Fig. 3).

Both the Forest Sands and the Upper Cruse Sands are lenticular and

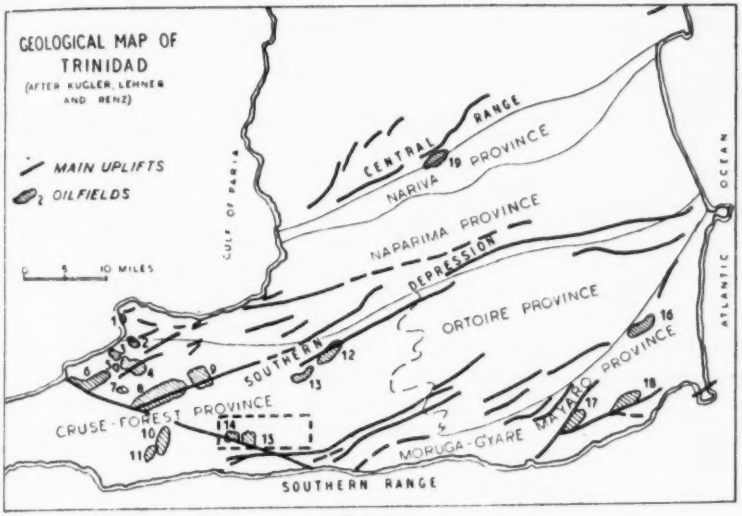

FIG. 1.

THE MAIN PRODUCING AREAS OF SOUTHERN TRINIDAD.

The area discussed in this paper is that within the dotted oblong.

Legend.

Oilfields:

1. Brighton.
2. Vessigny.
3. Kerr-Trinidad Oilfields.
4. Parrylands.
5. Cruse.
6. Point Fortin.
7. Point Fortin Central.
8. Forest Reserve.
9. Apex.
10. Trinidad, Petroleum Development, Palo Seco.
11. S.T.O.L. Palo Seco.
12. Barrackpore—Wilson.
13. Penal.
14. Quinam.
15. Morne Diablo.
16. Lizard Springs.
17. Goudron.
18. Beach, G'yare.
19. Tabaquite.

poorly developed, and, in general, afford poor reservoir conditions due to this lack of continuity.

The Middle Cruse Sands, however, form a well-defined sand zone, and within the limits of the area behave as sheet sands. The continuity, and consequently the correlation, is good throughout the greater part of the area, and regular variation in development is found. The Middle Cruse sand zone thins out eastward beyond Well MD.19 so that in Wells MD.23, 5, and 7 the sands cannot be identified with any certainty. Westward, and northward into the Siparia syncline, the sand zone appears to have considerable extension.

The Middle Cruse Sands can be divided into five well-defined sand layers,

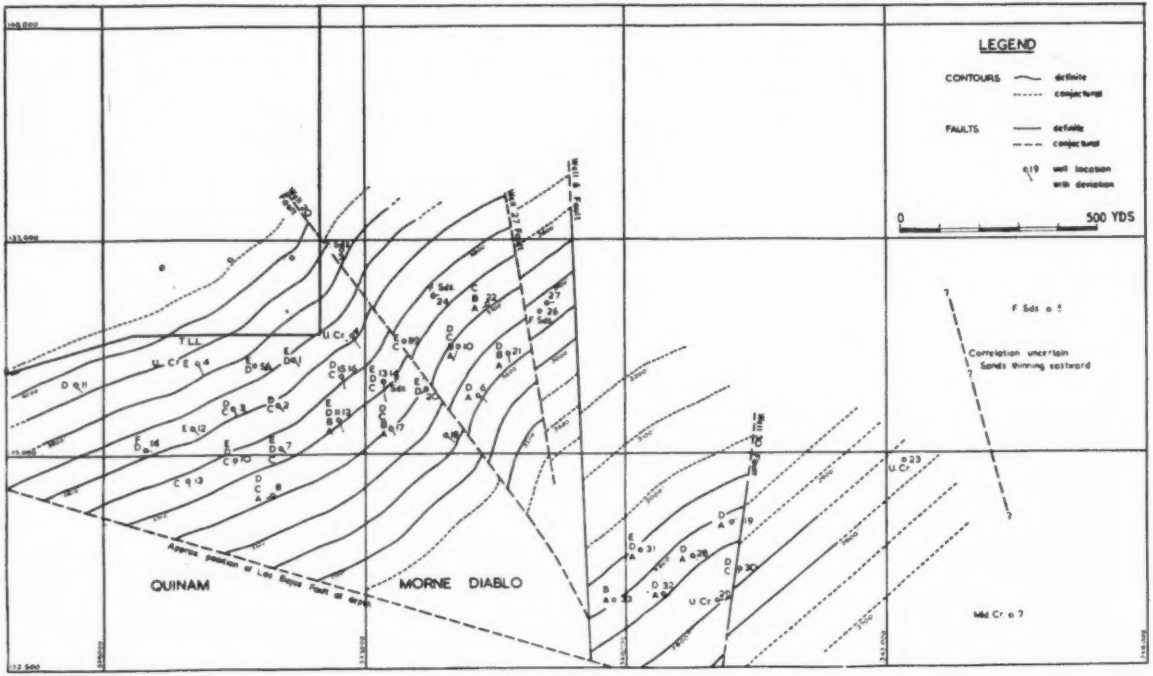

FIG. 2.

T.L.L./S.T.O.L. MORNE DIABLO AND T.L.L. QUINAM FIELDS, STRATUM CONTOUR MAP OF THE MIDDLE CRUSE SAND ZONE.

Contour interval 100 ft. Author, K. W. Barr.

Note.—Contour horizon = top of "A" sand of Norah Wilson and Quinam west blocks. Owing to the thinning out of the "A" sand eastward, a higher horizon, average 120 feet above top "A" sand was used for wells east of the Well 6 fault. On the map the contours are shown for the "A" sand throughout.

with a sixth layer occurring occasionally at the top; these are lettered A to F from the base upwards.

The "A" Sand shows the most consistent development and is usually about 50 ft thick, with a maximum thickness of 80 ft. The "B" Sand is thin, varying from 15 to 20 ft, and in some areas it is entirely absent. The "C" and "D" Sands are more variable, ranging from 20 to 80 ft each, the variations in thickness being independent of each other. The "E" Sand is more irregular in development; it is usually 30 to 50 ft thick and reaches a maximum of 100 ft, but it tends to be lenticular and may be absent altogether. The "F" Sand is markedly lenticular and occurs in only a few wells. The majority of the wells are producing several sand zones together, and only three wells are at present completed in a single sand.

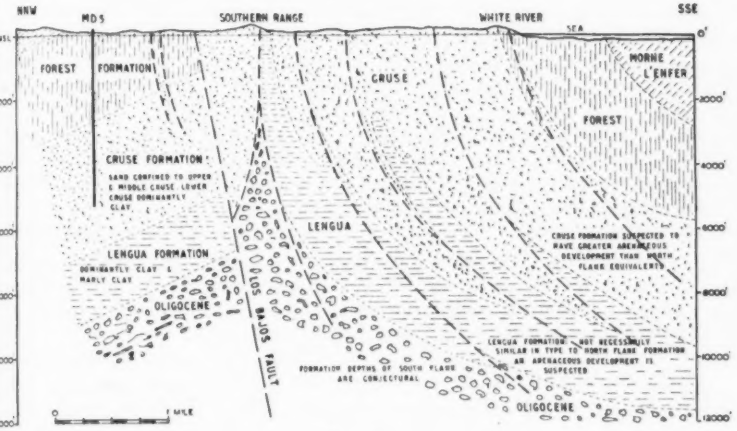

FIG. 3.

A STRUCTURAL INTERPRETATION OF THE SOUTHERN RANGE ANTICLINE, MORNE DIABLO AREA. (*After G. Huggins.*)

The production history of the field has been governed by an active water drive, and it has been possible to trace the advance of the edge-water in the various sands. The maximum advance is recorded in the "A" Sand, which is now producing from only a limited number of upflank wells. Gas-cap conditions are found upflank against the fault and set a limit to development in that direction.

It has been commonly assumed that the Los Bajos Fault is a major feeder fault and has, to a large degree, been responsible for the oil impregnation of sands adjacent to it. This area, particularly in the case of the Middle Cruse Sands, offers an opportunity to investigate this hypothesis, for it would be expected that the sheet-like Middle Cruse sands would be invaded by the migrating oil, whereas the discontinuous sands of the Upper Cruse and Forest Formations should be unaffected, except possibly in those sands actually in contact with the fault.

Analysis of the Oils.

Samples from all the producing wells in the field were drawn over a period of ten months (May 1944 to February 1945). In some cases wells had been closed in and, where it was not possible to reopen these, earlier samples (drawn during the main survey of the island during 1941–43) were used. When possible, however, wells were reopened and kept on production for one month before samples were drawn.

The samples were analysed by the methods previously described [6] with the following exception. The " characteristic graph," obtained by precise fractionation of the secondary distillate and graphical representation of the analytical data of the so-obtained fractions, proved to be inconvenient when applied to a survey including a large number of oils. Moreover, the occurrence of azeotropes precluded any reliable analysis of the hydrocarbon types. Accordingly the secondary distillate was first freed from aromatic hydrocarbons by percolation through columns packed with silica jel. The aromatic-free elutriate was then fractionated through columns, packed with 4 ft of 1-in dia Stedman packing, under standard conditions of reflux ratio and boil-up rate, and the distillate collected in fractions equal to 1 per cent by volume of the charge. The physical constants of the fractions (D_4^{30}, N_D^{30}, A.Pt °C) were recorded. Calculation of the paraffin–naphthene content and estimation of the hydrocarbon composition was achieved by comparison of the physical constants of the fractions with the published data for pure hydrocarbons. These results were then summarized to give the following parameters used in this survey.

1. *Secondary Distillate.* Per cent by volume of crude oil of material boiling between 60° and 160° C. Material boiling below 60° C was not included, since losses by evaporation during sampling and storage of the sample may affect this figure.

2. *Paraffin, Naphthene, and Aromatic Hydrocarbons.* Expressed as volume per cent of secondary distillate. Aromatic hydrocarbons were determined by extraction of the secondary distillate as previously described.[5,6] Paraffin and naphthene hydrocarbon percentages were obtained by the precise fractionation of the aromatic-free secondary distillate.[6]

3. *Benzene, Toluene, and Xylenes.* Volume per cent of secondary distillate. Determined as described previously—the " xylene " figure includes ethylbenzene and the three xylenes. No attempt has been made in this survey to estimate these separately, although later work, using ultra-violet spectroscopic methods of analysis, has shown this to be feasible and of considerable interest.

4. *Ratio of* cyclo*Pentane Derivatives to* cyclo*Hexane Derivatives.* This figure is calculated from the detailed analysis. It is admittedly approximate and is used with due reserve. It refers only to the secondary distillate.

5. *Paraffin–Naphthene Ratio.* This figure is calculated from the detailed analysis, and also refers to the secondary distillate.

General Review of Analytical Data.

Forest Sands Oils. The analysis of the oils from the Forest Sands are given in Table V. Secondary distillate yields vary from 6·3 to 19·6 per

TABLE V.

Morne Diablo–Quinam Field.

Horizon :	Forest sands.									Lower cruse.
Well no.	MD.3.	MD.24.	MD.14.	MD.16.	MD.16.	Q.6.	Q.6.	MD.5.	MD.26.	Q.16.
Date drawn . . .	23.3.44.	15.9.44.	14.9.44.	7.2.45.	14.9.44.	12.8.44.	20.3.43.	22.4.43.	2.12.44.	3.11.42.
Secondary distillate, % on crude	7·92	10·4	6·3	14·0	19·2	16·7	19·61	8·43	18·3	10·45
Aromatics, % on sec. dist. .	24·4	18·9	15·5	15·6	14·0	13·8	14·1	6·1	3·2	7·4
Naphthenes, % on sec. dist. .	48·0	43·6	47·0	43·1	45·9	42·4	37·5	44·4	59·7	53·8
Paraffins, % on sec. dist. .	37·6	37·5	41·3	41·1	40·1	43·8	48·3	50·5	37·1	38·8
Benzene, % on sec. dist. . .	1·5	1·4	0·5	0·5	0·6	0·6	0·7	0·2	0·2	0·5
Toluene, % on sec. dist. . .	6·2	3·8	3·0	3·6	3·9	3·8	3·8	1·2	0·8	1·1
Xylenes, % on sec. dist. . .	12·0	9·5	9·2	8·4	6·6	6·9	7·2	2·8	1·0	3·8
C_6/C_5–naphthenes ratio . .	0·57	0·72	0·92	0·87	0·89	0·85	1·40	1·26	1·00	1·26
Paraffin–naphthene ratio .	0·57	0·86	0·80	0·96	0·87	1·03	1·29	1·11	0·62	0·72

cent, and the paraffin contents from 37·1 to 49·5 per cent. The divergent types of oil are noteworthy and suggest that the reservoirs are discontinuous. The naphthenic oils produced from Wells M.D.3, M.D.24, and M.D.14 are more aromatic than such oils previously encountered in this work. The oil from Well M.D.16 (1944) corresponds closely to the naphthenic Middle Cruse oils, but the oil from the same well in 1945 shows a divergence. The oil produced from Well Q.6 in 1943 is similar to the Upper Cruse oils from Wells Q.15 and M.D.9, while the oil from the same well in 1944 corresponds to the more naphthenic Middle Cruse oils. The oils from Wells M.D.5 and M.D.26 are unusual for the area.

Upper Cruse Sands Oils. The analysis of the oils from the Upper Cruse Sands are given in Table VI and again show marked differences.

TABLE VI.

Morne Diablo–Quinam Field.

	Upper cruse.						
Horizon : Well no. / Date drawn	Q.16b. 16.3.43.	MD.25b. 23.3.44.	MD.29b. 9.4.43.	MD.4. 12.9.44.	Q.15. 21.4.43.	MD.12c. 5.2.45.	MD.9. 26.2.45.
Secondary dist., % on crude	5·8	13·8	12·1	15·2	21·4	18·9	18·6
Aromatics, % on sec. dist.	5·7	16·7	20·4	14·4	14·7	12·5	15·6
Naphthenes, % on sec. dist.	62·3	50·2	44·5	47·2	44·9	42·8	32·9
Paraffins, % on sec. dist.	32·0	33·1	35·1	38·4	40·3	44·9	51·5
Benzene, % on sec. dist.	0·4	1·0	1·5	0·8	0·9	0·7	1·1
Toluene, % on sec. dist.	0·9	4·4	5·7	3·7	4·7	3·3	6·9
Xylene, % on sec. dist.	2·0	8·5	10·2	7·5	6·5	5·8	7·4
C_8 C_9–naphthenes ratio	0·85	0·83	1·01	1·01	1·62	0·96	1·49
Paraffin–naphthene ratio	0·51	0·66	0·79	0·81	0·90	1·05	1·56

The comparison of the oils from Wells M.D.9 and M.D.4, both of which border the Well 20 fault, is of particular interest. The oil of Wells Q.16b, M.D.23b, M.D.29b, and M.D.4 yield secondary distillates of decreasing paraffin–naphthene ratio, but no clear trend over the whole area can be discerned. Well M.D.12c produces an oil similar to the naphthenic Middle Cruse oil (cf. the oil from Well M.D.28. Table VII). The mixed Upper and Middle Cruse oil of Well Q4, is a typical Middle Cruse oil, and it is possible that production from the Upper Cruse Sand is limited.

Middle Cruse Sands Oils. With few exceptions the wells producing from the Middle Cruse Sand zone yield similar oils of the mixed-base type. The secondary distillates may be arranged in order of increasing paraffin–naphthene ratio to form the series given in Table VII. Apparent anomalies exist in the case of the oil from Well M.D.20 (located in the centre of the main producing area), and in the oils from Wells Q3, Q11 (outlying to the West), and Well Q16 (outlying to the East). The oil from Well M.D.20 differs from other Middle Cruse oils mainly in the low secondary distillate percentage and the high xylenes content. Wells Q3 and Q11 produce oils different from the neighbouring wells, Q3 oil having a low percentage secondary distillate of relatively high paraffin–naphthene ratio; Q11 oil having a low percentage secondary distillate of low paraffin–naphthene ratio.

TABLE VII.
Morne Diablo–Quinam Field.

TABLE VII.

Morne Diablo–Quinam Field.

Middle Cruse Wells.

Well no.	Q.9.	Q.11.	MD.31.	MD.33b.	MD.20b.	MD.15b.	Q.13b.	MD.13b.	Q.7.	Q.4.*	Q.5.	MD.21.	MD.17.	MD.8b.	Q.14b.
Date	4.5.44.	28.10.44.	19.9.44.	20.9.44.	15.9.44.	15.2.45.	26.10.44.	1.12.44.	24.10.44.	27.10.44.	12.8.44.	5.12.44.	13.9.44.	12.9.44.	1.12.44.
Secondary dist., % on crude	7·7	10·4	15·3	17·8	15·2	18·6	18·0	18·9	19·8	17·1	18·6	22·5	22·9	19·7	19·6
Aromatics, % on sec. dist.	23·0	15·5	13·9	14·3	15·8	14·5	13·6	13·2	13·0	12·8	12·1	11·5	12·4	12·7	12·2
Naphthenes, % on sec. dist.	44·0	47·6	45·7	45·3	44·2	44·7	44·9	45·5	44·9	45·1	44·8	44·3	44·4	44·0	43·2
Paraffins, % on sec. dist. .	33·0	36·9	40·4	40·4	40·0	40·8	41·5	41·3	42·1	42·1	43·1	44·2	43·2	43·3	44·6
Benzene, % on sec. dist. .	0·7	0·7	0·9	0·9	0·8	1·0	1·1	0·6	1·1	1·0	0·6	0·8	0·9	0·8	0·9
Toluene, % on sec. dist. .	1·7	3·7	3·5	4·1	4·1	4·3	4·1	3·9	4·0	3·3	2·3	3·6	3·7	3·7	3·8
Xylenes, % on sec. dist. .	14·0	7·7	6·2	6·7	8·0	6·7	5·9	6·9	5·6	6·5	5·9	5·3	5·8	5·8	5·4
C_6/C_5-naphthenes ratio .	0·99	0·83	0·97	1·03	1·04	1·07	0·86	1·04	0·99	0·93	1·07	0·89	1·01	0·89	1·02
Paraffin–naphthenes ratio	0·75	0·78	0·88	0·89	0·90	0·91	0·92	0·91	0·94	0·93	0·96	1·00	0·97	0·98	1·03
Sands open for production	? —	—	E	—	E	—	—	E	E	E	E	—	—	E	"F"
	? D	D	D	—	D	D	—	D	D	—	D	D	D	—	D
	? —	—	—	—	—	C	C	C	C	—	—	—	C	C	—
	? —	—	—	B	—	—	—	—	—	—	—	B	B	—	—
	? —	—	A	—	—	—	—	—	—	—	—	A	A	—	—

Well no.	Q.3.	Q.2.	MD.28.	MD.10.	Q.1b.	Q.12b.	Q.10b.	MD.6.	MD.7.	MD.32.	MD.22b.	MD.19.	MD.11.	Q.8.
Date	27.10.44.	14.11.44.	19.9.44.	13.9.44.	2.12.44.	26.10.44.	1.11.44.	14.7.43.	21.4.43.	5.3.43.	25.3.43.	5.3.43.	26.2.43.	17.3.43.
Secondary dist., % on crude	11·3	19·9	19·8	22·6	20·4	20·3	21·2	21·2	20·15	17·6	22·0	18·1	22·8	24·1
Aromatics, % on sec. dist.	12·8	14·4	13·1	13·1	13·7	12·8	10·9	13·3	13·4	13·9	13·9	16·2	14·6	14·9
Naphthenes, % on sec. dist.	43·3	43·4	43·5	41·7	41·5	41·4	42·1	38·9	38·6	37·9	36·4	32·6	32·4	29·4
Paraffins, % on sec. dist. .	43·9	42·2	43·4	45·2	44·8	45·7	47·0	47·8	48·0	48·2	49·7	51·2	53·0	55·7
Benzene, % on sec. dist. .	0·6	0·9	0·9	0·6	1·0	0·9	0·7	0·9	1·1	0·7	0·8	1·4	0·9	1·5
Toluene, % on sec. dist. .	4·6	4·1	4·2	3·7	4·0	3·8	4·0	4·0	4·4	4·6	4·7	4·6	4·3	5·2
Xylenes, % on sec. dist. .	6·2	6·4	5·8	6·1	6·5	5·8	3·8	6·6	6·0	7·5	6·5	7·7	7·2	6·2
C_6/C_5-naphthenes ratio .	1·00	1·00	0·92	0·86	1·03	0·94	0·90	1·30	1·00	1·18	1·03	1·23	1·09	1·13
Paraffin-naphthenes ratio	1·01	0·97	1·00	1·08	1·08	1·10	1·12	1·32	1·24	1·28	1·56	1·57	1·57	1·89
Sands open for production	—	—	—	—	E	E	E	—	?	—	—	—	E	—
	D	D	D	D	D	—	D	D	?	D	—	D	D	D
	C	C	—	C	—	—	C	—	?	—	C	—	—	C
	—	—	—	B?	—	—	—	—	?	—	B	—	B	—
	—	—	A	A	—	—	—	A	?	A	A	A	A	A

* Middle and Upper Cruse open to production.

In general, however, the Middle Cruse oils yield secondary distillates of the mixed-base type with a paraffin content of between 40 and 50 per cent, in a yield of 15 to 20 per cent on the crude, and are broadly similar. However, it is believed that the differences recorded in Table VII are significant, and an attempt has been made to relate these to the geological factors. In the first place, from the general similarity of the oils, a fair degree of continuity of the reservoirs may be inferred, and, assuming this to be so, attempts were made to interpret the results both on the basis of the existing structural pattern, and then allowing some degree of modification. This, however, did not yield satisfactory results, and unwarranted structural modifications would have been required to explain certain anomalies notably in the case of Wells M.D.20, Q3, and Q11.

A further study of the data indicated that each of the five Middle Cruse Sands west of the Well 6 fault might be associated with a particular type of oil. This yielded consistent results, and the evidence is discussed below. The following assumptions are made : (1) that the sands are continuous within the limits of the area; (2) that tectonic elements which may be present have had no appreciable effect on the quality of the oil; (3) that the productivity of a given sand may vary from well to well.

In connexion with the last assumption it is also probable that productivity may vary in time, but the possible effect of this lies outside the scope of this discussion.

Tables VIII, IX, X, and XI present a re-arrangement of the parameters from Table VII for the purpose of this discussion. The wells can be

TABLE VIII.

Middle Cruse Wells Producing from Single Sands.

Well . . . . Date	Q.13b. 26.10.44.	Q.11. 28.10.44.	Q.12b. 26.10.44.
Secondary dist., % crude . . .	18·0	10·4	20·3
Aromatics, % on sec. dist. . . .	13·6	15·5	12·8
Naphthenes, % on sec. dist. . . .	44·9	47·6	41·5
Paraffins, % on sec. dist. . . .	41·5	36·9	45·7
Benzene, % on sec. dist. . . .	1·1	0·7	0·9
Toluene, % on sec. dist. . . .	4·1	3·7	3·8
Xylenes, % on sec. dist. . . .	5·9	7·7	5·8
C_6/C_5–naphthenes ratio . . .	0·86	0·83	0·94
Paraffins–naphthenes ratio . . .	0·92	0·78	1·10
Producing sands	C	D —	E —

divided into groups according to the sand or sands which are open to production. It is important to note that, unfortunately, only three wells are producing from a single sand.

Wells Producing from the Single Sands C, D, or E (Table VIII). When

TABLE IX.

Middle Cruse Wells Producing from Pairs of Sands.

Well	MD.33b.	MD.28.	MD.32.	MD.19.	MD.6.	MD.15b.	Q.2.	Q.3.	MD.8b.	MD.20b.	Q.1b.	Q.5.	Q.14b.
Date	20.9.44.	19.9.44.	5.3.43.	5.3.43.	14.7.43.	15.2.45.	4.11.44.	27.10.44.	12.9.44.	15.9.44.	2.12.44.	12.8.44.	1.12.44.
Secondary dist., % on crude	17·8	19·8	17·6	18·1	21·2	18·6	19·0	11·3	19·7	15·2	20·4	18·6	19·6
Aromatics, % on sec. dist.	14·3	13·1	13·9	16·2	13·3	14·5	14·4	12·8	12·7	15·8	13·7	12·1	12·2
Naphthenes, % on sec. dist.	45·3	43·5	37·9	32·6	38·9	44·7	43·4	43·3	44·0	44·2	41·5	44·8	43·2
Paraffins, % on sec. dist.	40·4	43·4	48·2	51·2	47·8	40·8	42·2	43·9	43·3	40·0	44·8	43·1	44·6
Benzene, % on sec. dist.	0·9	0·9	0·7	1·4	0·9	1·0	0·9	0·6	0·8	0·8	1·0	0·6	0·9
Toluene, % on sec. dist.	4·1	4·2	4·6	4·6	4·0	4·3	4·1	4·6	3·7	4·1	4·0	2·3	3·8
Xylenes, % on sec. dist.	6·7	5·8	7·5	7·7	6·6	6·7	6·4	6·2	5·8	8·0	6·5	5·9	5·4
C_6/C_5-naphthenes ratio	1·03	0·92	1·18	1·23	1·30	1·07	1·00	1·00	0·89	1·04	1·03	1·07	1·02
Paraffin-naphthenes ratio	0·89	1·00	1·28	1·57	1·32	0·91	0·97	1·01	0·98	0·90	1·08	0·96	1·03
Producing sands	| | | B	| D | | A	| D | | A	| D | | A	| D | | A	| D | C | |	| D | C | |	| D | C | |	E | C | |	E | D | |	E | D | |	"F" | D | |

the nature of the secondary distillates characteristic of oils from wells perforated opposite single sands—Wells Q.13, Q.11, and Q.12b—is compared with the average secondary distillate from oils produced from the Middle Cruse Series, it is clear that the Sand C oil distillate is slightly more naphthenic than the average and (as would be expected from previous analyses of Trinidad crudes) in slightly lower yield. The Sand D oil yields a secondary distillate with a marked naphthenic character and an aromatic content unusually high for its paraffin content. Sand E oil, on the other hand, lies on the paraffinic side of the average.

Wells Producing from Two of the Sands C, D, and E (*Table IX*). The wells producing from two of the three upper sands of this series fall into three groups. The wells producing from the C and D Sands yield oils intermediate in character between the oils from Well Q.13 (Sand C only) and Well Q.11 (Sand D only), and a similar state of affairs persists when the other pairs of sands are considered. It must be inferred, however, that the relative production from each sand of a pair is not the same in each well. The important parameters in comparing the C and D sand oils are the secondary-distillate percentages and the total xylene contents. It is obvious from such a comparison that the oils from Wells M.D.15 and Q.2 are more akin to the oil from Well Q.13 than to that from Well Q.11. It must be assumed, therefore, that production is mainly from the C sand. The data from Well Q.3 do not fall into place satisfactorily, the yield of secondary distillate suggests Sand D is the main producer, whereas the paraffin and aromatic contents both lie on the paraffinic side of Sand C oils.

The difference between the oils from Sands C and E is more clearly perceived in the paraffin–aromatic ratios. It will be seen that the oil from Well M.D.8 is intermediate in character between the typical oils and that Sand E appears to be the main producer.

The difference between the oils from the D and E sands is emphasized by the secondary-distillate percentages and the paraffin and xylene contents. The chemical evidence suggests therefore that production from the D sand decreases along the series: M.D.20, Q.5, and Q.1b. The similarity of the secondary distillate from Well Q.14b (producing from Sands D and F) to that typical of Sand E suggests that production from Sand D is limited and that the oils from Sands E and F are similar in nature.

Wells Producing from all the Sands C, D, and E (*Table X*). In the more complex mixtures it is difficult to identify the effect of the different oil types. A large proportion of the typical Sand D oil would be indicated by a low percentage of secondary distillate. Sand E oils would, if in large proportion, result in high paraffin–aromatic ratios. Sand C oils being intermediate in character between the other two are more difficult to identify. High benzene and toluene figures are the best guides.

The oils produced from Wells M.D.13 and Q.7 are of the naphthenic type, but, apart from the low benzene content, there is no chemical evidence which indicates production from Sand D.

Well Q.10 produces a paraffinic oil more akin to the oils from Sand A. The suggestion is that in this area the production is almost entirely from the E sand and that Well Q.10 is producing from the same reservoir as Well Q.12.

Production from the A and B Sands (*Tables IX and X*). So far it has

TABLE X.

	Middle Cruse Wells producing from three sands.						
Well Date	MD.22b. 25.3.43.	MD.21. 5.12.44.	Q.8. 17.3.43.	M.D.31. 19.9.44.	M.D.13b. 1.12.44.	Q.7. 24.10.44.	Q.10b. 1.11.44.
Secondary dist., % on crude	22·0	22·5	24·1	15·3	18·9	19·8	21·2
Aromatics, % on sec. dist.	13·9	11·5	14·9	13·9	13·2	13·0	10·9
Naphthenes, % on sec. dist.	36·4	44·3	29·4	45·7	45·5	44·9	42·1
Paraffins, % on sec. dist.	49·7	44·2	55·7	40·4	41·3	42·1	47·0
Benzene, % on sec. dist.	0·8	0·8	1·5	0·9	0·6	1·1	0·7
Toluene, % on sec. dist.	4·7	3·6	5·2	3·5	3·9	4·4	4·0
Xylenes, % on sec. dist.	6·5	5·3	6·2	6·2	6·9	5·6	3·8
C_6/C_5-naphthenes ratio	1·03	0·89	1·13	0·97	1·04	0·99	0·90
Paraffins-naphthenes ratio	1·56	1·00	1·89	0·88	0·91	0·94	1·12
Producing sands	— — C B A	— D — B A	— D C — A	E? D — — A	E D C — —	E D C — —	E D C — —

been possible to develop the discussion by allocating specific oils to the three upper sands in the Middle Cruse Series. However, the allocation of oil types to the A and B sands becomes more difficult, as none of the wells examined produces from these sands alone. Moreover, three of the five wells which produce from the A sand and one other sand lie to the east of the Well 6 fault. The method of attack has been first to consider the data for Well M.D.6 (Sands A and D, Table IX), which lies to the west of the Well 6 fault, relative to the data for Well Q.11 (Sand D only). Since the secondary distillates from the D sand oils are essentially naphthenic, it must be inferred that the A sand oils account for the paraffinicity of the secondary distillate from the oil of Well M.D.6. Even if the production is mainly from the A sand it is clear that the Sand A oil is the most paraffinic in the area. It is probable, however, that there is some production from Sand D, in which case the A sand may be even more paraffinic than that represented by the secondary distillate of the oil from Well M.D.6.

This estimate of the type of oil produced from the A sand is confirmed when the data relative to the oil from Well Q.8 are compared with those of the mixed C and D oils. Here the effect of adding production from the A sand has been to increase markedly the yield and the paraffin content of the secondary distillate.

When the wells east of the Well 6 fault producing from the A sand are considered in the light of these deductions it is found that the secondary distillates from the oils of Wells M.D.19 and M.D.32 are consistent with the assumption of a paraffinic oil in the A sand and a naphthenic oil in the D sand, and it is inferred that in the case of Well M.D.19 the A sand is contributing the bulk of the oil produced.

The character of the B sand is more obscure. The data relative to Well M.D.33 (A and B sands) suggests that the secondary distillates from Sand B oils tend towards the type of secondary distillates characteristic of Sand D (*i.e.*, low in yield and naphthenic) or, if the production from A sand is small, at least to the Sand C type. There are no wells west of

the Well 6 fault which produce from the B sand together with one other sand, but the naphthenic nature of the Sand B oil is supported by a comparison of data from Well M.D.21 oil (Sands A, B, and D) with that for the usual mixture from Sands A and D. The data relative to Well M.D.22 suggest that the production comes mainly from Sand A. Any other explanation would require a high-yield, paraffinic, secondary distillate from crudes from Sand B.

The More Complex Mixtures (*Table XI*). Wells M.D.17 and M.D.10,

TABLE XI.

	Middle Cruse Sands producing from four sands.			Other wells.		
Well	MD.17.	MD.10.	MD.11.	Q.4.*	MD.7.	Q.9.
Date	13.9.44.	13.9.44.	26.2.43.	27.10.44.	21.4.43.	4.3.44.
Secondary dist., % on crude	22·9	22·6	22·8	17·1	20·15	7·7
Aromatics, % on sec. dist.	12·4	13·1	14·6	12·8	13·4	23·0
Naphthenes, % on sec. dist.	44·4	41·7	32·4	45·1	38·6	44·0
Paraffins, % on sec. dist.	43·2	45·2	53·0	42·1	48·4	33·0
Benzene, % on sec. dist.	0·9	0·6	0·9	1·0	1·1	0·7
Toluene, % on sec. dist.	3·7	3·7	4·3	3·3	4·4	1·7
Xylenes, % on sec. dist.	5·8	6·1	7·2	6·5	6·0	14·0
C_6/C_5-naphthenes ratio	1·01	0·86	1·09	0·93	1·00	0·99
Paraffins–naphthenes ratio	0·97	1·08	1·57	0·93	1·24	0·75
Producing sands	— D C B A	— D C B? A	E D — B A	E — — — —		

* Middle and Upper Cruse open to production.

producing from the four lower sands, give similar secondary distillates approximating in character to the average secondary distillate characteristic of the entire area. However, the yields are high. Comparison with the secondary distillate from Well Q.8 oil confirms the naphthenic character of the B sand oil. The high yields of secondary distillate suggest that production from the upper sands is limited. Comparing these oils with that from Well M.D.11 it is apparent that absence of production from Sand C and replacement by production from Sand E has produced the expected increase in paraffinicity of the secondary distillate.

Other Middle Cruse Wells (*Table XI*). The oils from Wells M.D.7 and Q.9 (4.3.44) are apparently produced from unrelated reservoirs, and the data do not contribute to the discussion of characteristic oils.

The foregoing discussion leads to the hypothesis that definite oil types can be allocated to each of the sands in the Middle Cruse Horizon. Sand A oil is paraffinic with a high secondary distillate yield, Sand B oil naphthenic with a low yield of secondary distillate, Sand C oil is less naphthenic and yields more distillate, while Sand D oil is probably more naphthenic than Sand B and the distillate is in low yield. Sand E oil is on the paraffinic side of the average, and Sand F oil is similar; both give high yields of secondary distillate. In some cases, although the well casing may be perforated opposite a given sand, it appears that production may be restricted.

It is possible that the oils identified with the various sands may differ slightly on either side of the Well 6 fault, but there is not sufficient evidence that on chemical grounds a discontinuity would be postulated.

The anomalies, which are only too obvious when the horizon is treated as one reservoir, are reduced to those shown by Well Q.3 and the minor ones shown by Well M.D.28 in the foregoing treatment. As a corollary, it appears that the individual sands may well be continuous throughout the area of development east of the Well 6 fault, and it seems unlikely that the minor faults play any marked part in the distribution of the oils.

Correlation of Chemical and Geological Evidence.

The survey has yielded interesting results which suggest conclusions of wide importance. As would have been expected, the lenticular Upper Cruse and Forest Sands yield a variety of oil types unrelated to one another or to the structural elements. The Middle Cruse Sands, which display good reservoir continuity, yield a broadly similar oil of mixed-base type which does not appear to be related to the established structure of the area. No trend in properties can be related to the Los Bajos Fault or any of the subsidiary faults. This does not rule out the possibility of original impregnation by way of the Los Bajos Fault if it is assumed that the original impregnation took place into oil-free sands, or, alternatively, that mixing in the sands had reached equilibrium. It has been noted in other areas that where fault impregnation is suspected, changes in the character of the oil have been found associated with the faulting, although, on present evidence, this should not be taken as a general rule. On the basis of the evidence of the Middle Cruse oils, therefore, the possibility of impregnation by way of the Los Bajos Fault cannot be ruled out. Some additional evidence is provided by the Upper Cruse oils, for Well M.D.29b, which is close to the fault, yields an oil different from the Middle Cruse types but rather similar to that of the Upper Cruse Well M.D.23b considerably farther away from the fault, which argues against fault impregnation in this sand.

The balance of the evidence points to the conclusion that the Los Bajos Fault has not behaved as a major feeder fault in this area, but that it has acted passively as a seal, trapping the oil moving upward across the Morne Diablo flank of the Southern Range uplift. The fact that there is an active water drive in the Middle Cruse Sands means that the sand zone must have considerable extension downflank towards the Siparia syncline, and it is probable that the initial flushing of the sands provided the oil of the Morne Diablo and Quinam Fields.

The variation of the Middle Cruse oils is explained by the hypothesis that the individual sands contain different oils, which produce a mixed oil of varying properties according to the number of sands open to production in a particular case. This is of considerable theoretical and practical importance, for if it can be conclusively established that sand layers so close together as the individual sands of the Middle Cruse sand zone can contain different oils, the source of these oils poses a complex problem.

The fact that the subsidiary faults are not reflected in the oil distribution,

even in the case of the Well 6 fault which is sufficiently large to throw the Middle Cruse Sands out of contact in the area of development, is of considerable interest and has a bearing on the source of the impregnation. These subsidiary faults die out northward into the synclinal region, and if the oil is assumed to have migrated along the Middle Cruse Sands moving upwards from the lower parts of the flank towards the higher, then there is no reason why the faults, which merely form, as it were, compartments at the upper end of the reservoir, should modify the distribution.

Derivation of Oil in Discontinuous Reservoirs.

The variety of oils found in the lenticular sands of the Forest and Upper Cruse sand zones would suggest that each oil is indigenous to the sand or enclosing shale. Commenting upon the origin of oils found in the lenticular sands associated with the unconformity at the top of the Arbuckle limestone, the Tulsa Geological Research Committee[3] suggest that "If the oil migrated over any considerable distance throughout a sizeable area—many pools in a given area should contain similar oil. The fact that the oils in these zones are not similar but are highly variable from pool to pool suggests that such migration has not taken place." For this reason these authors consider the oils in such discontinuous reservoirs to be indigenous to the sand in which they are found and attribute the differences in oil types to differences in source material and environment. Examination of the Forest and Upper Cruse sands and shales does not suggest any marked variation in source material from sand to sand, and it is difficult to imagine that the environment of the sands would vary to any appreciable degree. The view of the Tulsa Geological Research Committee that a variety of oils in lenticular sands is evidence against migration is only acceptable where, as in the case of the oils at the top of the Arbuckle limestone, geological evidence is available to suggest that a variety of source materials and/or environments is possible.

If a series consisting mainly of sand lenses is imagined to overlie the source series, from which the oil has migrated during compaction, it is probable that the first oil to enter the sand series will have been derived from the part of the source rock which is most compacted—that is, the basal part. Ultimately it is probable that this oil will be trapped at the top of the sand series. Thus the oil in the upper sands will have migrated through more clay than the oil which was formed later and accumulated in the lower series. There is no reason to suppose that the oil formed in the later stages of compaction should be identical with that formed in the early stages. Although there is little information available on the relative rates of sedimentation, oil formation, and oil migration, it is conceivable that variation in these factors, together with possible variations in source material, may result in more than a single type of oil arising in any one source series.

In the case of the Forest and Upper Cruse sand oils, further investigation of the enclosing shales and of the extension of the series into the Siparia syncline is desirable. In general, it may be noted that chemical evidence alone is unable to differentiate between migrating or indigenous oils.

Multiple Oil Horizons.

The changes in the character of the oils of the Middle Cruse sand zones as the series is ascended, may be summarized as follows :

A. Paraffinic oil with high secondary distillate yield.
B. Naphthenic oil with low secondary distillate yield.
C. Less naphthenic than " B " oil.
D. More naphthenic than " B " oil.
E. Paraffinic oil.
F. Paraffinic oil.

These changes are incompatible with the theory of a single oil migrating upwards and being altered by adsorption, filtration, etc. Nor can they be reconciled with the view that the variations are due to the effect of different depths of burial. It is more probable that each oil has a separate source rock, and this source rock is the shale underlying each individual sand. As previously mentioned these shales are extremely thin, and it is difficult to see how they would have supplied the oil found above them unless it is assumed that they have considerable extension into the Siparia syncline. This assumption best fits the facts here presented, but further investigation is necessary before it can be accepted.

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Discussion.

The President (Mr E. A. Evans): This is the first time that we have had the opportunity of seeing Mr Gibson with us since he was here on a recent historic occasion, when we presented to him the Redwood Medal. I think it would be a pleasant gesture to ask him whether he would care to open the discussion on the paper we have heard presented.

Mr H. S. Gibson: I have listened to the presentation of the paper with very great interest indeed, for it introduces to me variations in the type of crude of an extent which is completely new to me. I have been concerned throughout the whole of my time in the industry with oils in large limestone reservoirs, where the crude itself is extremely uniform throughout a large structure of many miles in extent, and where even between the different structures stretching over 200 or 300 miles of country there is no great variation, except to a small extent in the lighter ends, which can be accounted for in the main, I think, by the difference in the quantities of gas held in solution, and by loss of gas through seepage.

The problem we have heard of to-night has been presented in great detail, and it seems to me of extraordinary interest; but I am afraid that I cannot offer any ideas and do not feel competent even to ask questions. I am waiting with interest to hear questions which others may put to Dr Morton.

However, in considering variations in the types of crude, I do not think we should under-rate the possibility that they may be due to migration. I am inclined to think that oil is never truly static in underground reservoirs. I feel sure that in Iran, for instance, we have both lateral and vertical movement. At one time the oilfields have probably been under very deep cover, and the removal of part of the cover at one point would cause lateral rather than vertical movement. Again, erosion immediately above the reservoirs would cause a tendency to vertical seepage, and for oil to be moved back again into reservoirs from which it had previously migrated.

If this is so and we could trace the pre-history of reservoirs, we might have some indication of how these variations in oils have arisen.

Mr T. Dewhurst (Past-President): With regard to the different oils from the Middle Cruse Sands, the authors state that "It is more probable that each oil has a separate source rock, and this source rock is the shale underlying each individual sand. As previously mentioned these shales are extremely thin, and it is difficult to see how they would have supplied the oil found above them unless it is assumed that they have considerable extension into the Siparia syncline." Such lateral extension is possible, and even probable, but nevertheless the shales are few in number and also are very thin. Moreover, the authors seem to favour the view that source rocks are not rich in organic matter. It seems doubtful, therefore, if the thin shales could have produced all the oil which exists in the Middle Cruse Sands.

In regard to great depth of burial of source rocks as a factor in the origin of oil, it is important to note that the deposition of sediment is very slow, and that the time required for the deposition of sediment equivalent to 1 ft of strata is of the order of a thousand years. It follows that millions

of years must elapse before a newly deposited source rock can be subjected to considerable temperatures and pressures due to super-incumbent strata. It is noteworthy in this connexion that a rich oil series usually forms part of a very thick sedimentary series. For example, in Burma there are more than 50,000 ft of Tertiary strata, and in Assam the Tertiaries are almost as thick as in Burma. Similarly, thick successions of strata occur in many other petroliferous provinces. It follows that after a lapse of millions of years, source rocks may be subjected to considerable temperatures and pressures due to super-incumbent strata. Whether or not these physical conditions have any important bearing on the origin of petroleum is a moot point, but it is probable that they have an important influence on the migration of petroleum.

In some countries the evidence of extensive upward migration of petroleum is very impressive. For example, in the Khaur oilfield in the Punjab, productive oilsands occur throughout a range of about 5000 ft of Upper Murree beds of Miocene age, yet the whole of the oil has migrated upward from source rocks of Eocene age. Again, in the Digboi field of Assam, there are many oilsands in the Miocene Tipam Sandstones, which are completely barren of oil elsewhere, although they are well exposed for hundreds of miles. The conclusion is beyond doubt that the whole of the Tipam oil has migrated upward from older Tertiary source rocks. Moreover, in Rumania there are rich oil deposits in fresh-water beds of Pliocene age. Other examples of extensive upward migration of oil could be cited.

In the case of Trinidad, there are many possible, and even probable, source rocks of oil ranging in age from Lower Cretaceous to Middle Miocene. Indeed, almost all of the many argillaceous beds within this stratigraphical range have been considered to be probable source rocks of petroleum. These rocks have been subjected to very severe earth-movements, resulting in very steep folding, doubtless accompanied by much jointing and fissuring of the strata. Such conditions would be ideal for very extensive upward migration of oil from the older source rocks into the younger beds, and it would seem to be reasonable to assume that this is what took place. Indeed, the fact that oil indications occur at horizons above the youngest source rock shows that some upward migration of oil must have occurred.

In considering the nature of the Middle Cruse oils, it should be borne in mind that the oils of the older source rocks may have had very different characteristics; it might be unwise to assume that only one type of oil was formed in the many older source beds.

It is conceivable that the Los Bajos Fault, and also the smaller faults described in the paper, were the latest effects of the earth-movements, and that migration of the oil had in the main been completed before the faulting took place.

Professor F. H. Garner : I have found this paper particularly interesting in the way in which it has presented the various theories concerning the origin of petroleum. Such theories, based on chemical radioactive adsorption or on bacteriological assumptions, suffer from lack of knowledge of what happens in these processes over long periods of time. We have to deduce from experimental work carried out in a matter of hours or months what is likely to occur in millions of years. It is, however, likely that more

than one of these processes may be important in the formation of petroleum from vegetable or animal sources, according to the type of crude petroleum.

In reference to the discussion concerning the transformation of paraffins to naphthenes, if this does occur, it may be that sulphur compounds play an active part, since free sulphur is an effective dehydrogenating agent.

THE PRESIDENT: It would appear that Dr Morton and his colleagues have given us what might be called surprise information; at least it is so to most of us. Mr Dewhurst seems to be the only speaker capable of expressing any "sane" opinions on the subject. Mr Gibson, great authority that he is, openly confesses that he has neither a question to ask nor an observation to make, and I cannot help feeling that many of you, like me, feel precisely the same.

When I read the paper I was fascinated by it, and I confess that I felt horribly ignorant on the subject. I still find it very difficult indeed to follow the change from paraffinic to naphthenic. If anyone asked me to guess which way the reaction went, I should say that it was the other way—which shows how easily the untrained mind can be led astray.

DR MORTON, replying to the discussion, said: Several points have been raised to which I should like to reply. First to Mr Gibson. Although the type of oil occurrence dealt with in our paper is very different from the occurrence in large limestone reservoirs, I agree that it is a mistake to regard oil as a stationary substance, particularly in producing areas. In a previous paper [7] we have described the migration of an oil into producing sands, and we believe that this migration occurred as the result of reduction in pressures—due to production. It is the mobility of oil which makes the study of the origin of oil and the identification of possible source rocks so very difficult.

Before replying to Mr Dewhurst I must plead that I am not the geologist of the group—and cannot therefore speak with authority. I believe that one of the great difficulties in co-operative research of this type—involving several different groups of scientists—lies in the inability of the chemist or geologist to think in the language of the other scientist. During the early part of this work I remember discussing with one of our geologists the evidence for what he called "transformational migration." After much argument I discovered that by this he meant not the transformation of one type of oil into another type during migration—but simply the migration of oil across a formation. However, I think I can speak for my co-authors on certain of the points raised by Mr Dewhurst. We do not deny that the evidence for vertical migration of oils is very strong in many oilfields, nor do we suggest that "shallow depth of burial" is the only tenable theory. Rather we believe that each individual oilfield and oilsand within the field presents its own particular problem. A theory which satisfactorily explains the known facts concerning one field may completely fail when applied to another field. In earlier papers [5, 6] we have suggested that some of the oil found in the Miocene Beds in Trinidad has, in fact, migrated from a deeper—probably Cretaceous—source. In the case of the oils of the Morne Diablo–Quinam field we believed we would find positive evidence in support of this view. As we have stated the observed facts do not support the view that

the oils have migrated up the Los Bajos Fault, and indeed, it is difficult to reconcile the analyses we give with any theory other than that of indigenous origin. It is admitted that the conclusions are tentative. So far we know nothing of the organic content required in a shale in order that it should be a source rock. Nor do we have any idea of how much oil a given shale could have yielded. On these points and on many others much work is still to be done. In passing it might be noted that in at least one other area in Trinidad in which we anticipated finding evidence in support of vertical migration of oil our results again suggest an indigenous origin. In other areas of Trinidad, however, we believe we have definite evidence in support of the vertical migration of oils.

In reply to Professor Garner's comments it seems likely that all the processes he has mentioned may play a part in the genesis of oil. Our particular interest, however, has been with the history of the oil subsequent to its formation. It is probable that any alteration the oil may undergo in its movement from the source rock to the reservoir rock will be the result of physical rather than chemical processes.

Vote of Thanks.

THE PRESIDENT: We are under a special obligation to Dr Morton and his colleagues for having given us the privilege of hearing this very important and unusual paper, and I am sure it is the wish of all of us to accord them a very hearty vote of thanks for the trouble they have taken in preparing it.

(The vote of thanks was accorded with acclamation.)

CATHODIC PROTECTION AND ITS APPLICATION TO THE IRAQ PIPELINES.

By W. C. R. Whalley * (Associate Member).

Introduction.

Cathodic protection is a term applied to systems of electrical drainage whereby the metallic structure in question is maintained at a negative potential to the surrounding soil or water. In a properly designed and operated system the structure, which is usually of steel, is thereby protected and remains substantially free from corrosion as long as the potential is maintained.

The origin of cathodic protection may be said to be the work of Sir Humphry Davy, published in 1824 and 1825 in the *Philosophical Transactions* of the Royal Society. He had been called in by the Commissioners of the Navy Board to investigate the corrosion suffered by the copper with which ships' bottoms were sheathed at that time. In a series of large-scale trials on ships sailing to the West Indies and elsewhere, he was able to demonstrate that the copper sheath could be preserved intact by the use of an iron or zinc mass connected to it. In present parlance, this would be termed a sacrificial anode. Davy was concerned to strike a balance between over-protection which led to the formation of a film of carbonates of calcium and magnesium, and the excessive wastage which normally occurred. Over-protection gave an opening to barnacles and weeds which adhered firmly to the carbonate film. A suitable adjustment (around 1 per cent) of the ratio of iron-to-copper surface gave sufficient protection greatly to reduce the loss of copper, whilst still allowing sufficient wear to keep the surface bright. Davy specifically records the formation of deposits of calcium and magnesium carbonates on the copper when the proportion of iron became too high. Such deposits are frequently observed in the cathodic protection of bare metal, particularly in marine conditions, and probably play a part in polarization of the surface.

The use of suspended zinc anodes is a long-established means of controlling corrosion in boiler practice. Likewise, the protection of lead-sheathed telephone cable by electric drainage has been described in the literature.

The application of cathodic protection to large steel structures such as pipelines and tank bottoms has received but little attention in the United Kingdom. This particular art has, however, become of considerable importance in the United States and other big centres of the petroleum and natural-gas industries in which thin-walled steel pipes are commonly used. Contrariwise, in the water and coal-gas distribution systems of the United Kingdom thick-walled cast-iron pipes constituted the usual practice until quite recently. Likewise the pressures employed in Britain are usually low or negligible, and never approach those utilized in long-distance oil and

* Iraq Petroleum Co. Ltd., Tripoli, Lebanon.

natural-gas lines. In these latter, operating pressures frequently run from 700 to 1000 p.s.i., giving rise to fibre stresses in the pipe metal of between 20,000 and 30,000 p.s.i., that is to say, 60 per cent or more of the yield point of the pipe steel. Such pressures rapidly bring to light even the smallest leak. Furthermore, the financial and public-liability implications of leaks in the former industries are slight by comparison with the material loss and public damage which can be occasioned by serious leaks in high-pressure oil or gas lines.

The loss of pumping time involved in shutting down a large line in order to repair a corrosion leak results in a serious reduction in throughput. For instance, in the case of a 16-in line pumping, say, 4 million tons per year, a shutdown of 15 minutes represents the loss of 120 tons. If the line is pumping at sustained full throughput as many lines are to-day, such losses are irretrievable. In the petroleum industry the modern tendency is for pipelines to become larger in diameter; 24- and 30-in oil and gas lines are now commonplace. The repair of pipes of such a size and operating at high fibre stresses is by no means the simple matter which it is in the case of 10- and 12-in lines. The loaded weight of these large lines may render it impracticable to lift them out of the ditch, which virtually rules out their reconditioning by the usual means of welding patches over corroded areas. Moreover, the act of welding a patch on to such a line may very possibly give rise to dangerous stress concentrations, unless special precautions are taken. Thus, the extensive reconditioning of large-diameter buried pipelines seems out of the question. Accordingly, in areas where the possibility of soil corrosion is known to exist, the best preventative measures become an economic necessity.

The greater part of the mileage of trunk pipelines in the world is, of course, in the smaller sizes from 8 to 16 in. In these sizes reconditioning of a corroded line is technically quite feasible, and can be carried out without affecting throughput. However, the cost of such reconditioning is heavy, amounting at the present time in the United States to around $8000 per mile for a 12-in pipe. The great increase in the cost of reconditioning since 1940 has promoted interest in alternative methods of counteracting soil corrosion.

The possibilities inherent in the principles of cathodic protection began to be recognized in the pipeline industry during the early thirties. For a considerable time there was much scepticism as to the efficacy of cathodic protection, and indeed many of the early installations failed to give entirely satisfactory results, usually on account of improper design or poor maintenance. However, it eventually became evident that in corrosive soils systems of cathodic protection could be installed and operated at a small fraction of the cost of periodic reconditioning. To-day, considerable progress has been made in the art, and it can be said with confidence that a properly designed and maintained system of cathodic protection will preserve a buried steel structure intact for a very long if not indefinite period.

A typical cathodic protection installation is illustrated in Fig. 1. Essentially the arrangement is designed to flow low-voltage D.C. on to the buried pipeline or other structure. The anode is usually a bed of scrap iron buried in the ground nearby. The pipe is the cathode. The pipe will usually be coated, and in any case the steel is a very much better conductor

of electricity than the soil. In the result, the soil becomes positive to the pipe in the path of the current between the anode and the cathode. This path may be very extensive, in cases of good pipe coating as much as 100 miles of line has been protected by a single installation. Figures of 5 to 40 miles are more frequently encountered in practice.

It should be noted here that the economic significance of the electrochemical currents associated with pipeline corrosion is out of all proportion to their magnitude. A current of 1 amp flowing for one year represents the dissolution of 20 lb of iron. The disappearance of such a quantity of iron from one mile of pipe would be unnoticeable if evenly distributed. On the other hand, taking an extreme case, the loss of 20 lb of steel is equivalent to 1000 holes of $\frac{1}{2}$ in diameter in a pipe of 0·33 in thickness. In the Middle

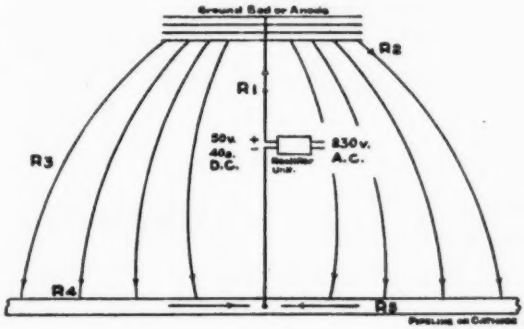


FIG. 1.

DIAGRAM OF CATHODIC PROTECTION UNIT.

Components of overall resistance ground bed to pipe :

R1. Resistance of conductor.
R2. Anode to soil contact resistance.
R3. Resistance of earth path.
R4. Pipe coating resistance.
R5. Resistance of pipe material.

East we have frequently observed currents of 1 to 3 amps and in an extreme case 8 amps, flowing in the pipes. Such currents are often ephemeral and change direction whilst under observation ; nevertheless, whilst flowing they do damage.

The potential between the pipe and the soil is generally employed as the criterion of a satisfactory installation. However, the potential of the pipe is itself only slightly affected. It is the soil with its much greater resistance which undergoes a change of potential.

THE CONTROL OF CORROSION BY CATHODIC PROTECTION.

Without going at all deeply into the very extensive theories concerning the mechanism of corrosion, it may be said that the electrochemical oxidation of iron involves an anode and a cathode (Fig. 2) connected by a metallic and a solution circuit respectively. The oxidation of iron at the anode may

be considered as involving the passage of a stream of electrons through the metal and an equivalent stream of positively charged ions through the solution. Both the electrons and ions flow by their respective paths to some cathodic area where neutralization may be effected and the circuit completed.

There has been considerable discussion of the precise mechanism of cathodic protection, but agreement is not general. From one point of view it would appear that the process may be regarded quite simply as the imposition of a negative potential between the metal and the solution sufficient to suppress the flow of positively charged ions from the anode, thereby bringing the process of electrochemical corrosion to a standstill. From

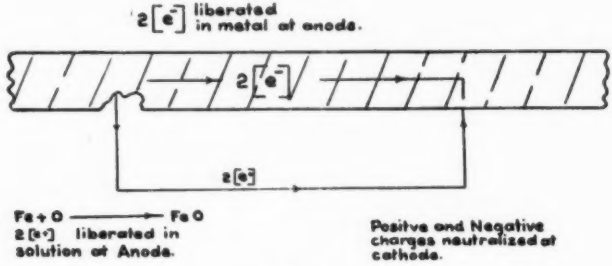

2[e⁻] liberated in metal at anode.
2[e⁻]
2[e⁻]
Fe + O ——→ Fe O
2[e⁻] liberated in solution at Anode.
Positve and Negative charges neutralized at cathode.

FIG. 2.
CORROSION CELL.

this point of view we may say that an opposite potential is imposed across the pipe–soil boundary greater that the solution potential of iron. The actual value of the solution potential of iron varies, of course, with the solution with which it is in contact. Table I [1] shows the solution potentials

TABLE I.

Electrode Potentials at 25° C.

	E_0.		E_0.
K | K	−2·9241	Pb | Pb$^{\cdot\cdot}$	−0·122
Na | Na$^{\cdot}$	−2·7146	Pt (H_2) | H$^{\cdot}$ |	0·00
Mg | Mg$^{\cdot\cdot}$	−2·40	Cu | Cu$^{\cdot\cdot}$	+0·3441
Al | Al$^{\cdot\cdot\cdot}$	−1·70	Ag | Ag$^{\cdot}$	+0·7978
Zn | Zn$^{\cdot\cdot}$	−0·7618	Hg | $Hg_2^{\cdot\cdot}$	+0·7986
Fe | Fe$^{\cdot\cdot}$	−0·441	Pt | OH$'$ | O_2 |	+0·3976
Cd | Cd$^{\cdot\cdot}$	−0·4013	Pt | (H_2) | OH |	−0·8280
Ni | Ni$^{\cdot\cdot}$	−0·231		
Sn | Sn$^{\cdot\cdot}$	−0·136		

of a number of common metals in contact with their ions in a solution of unit activity. It will be seen that the solution potential of iron is around −0·4 to −0·5 V, measured with reference to a hydrogen electrode as zero. The usual standard used in field work is a copper–copper sulphate electrode

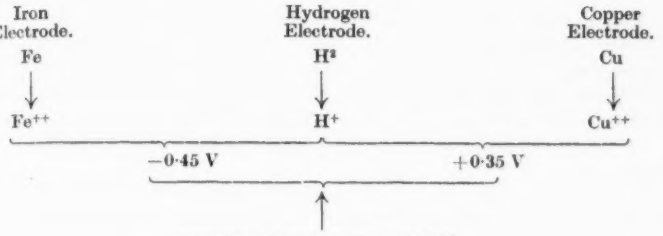


FIG. 3.

in which case the solution potential of iron is around −0·8 V as may be seen from Fig. 3.

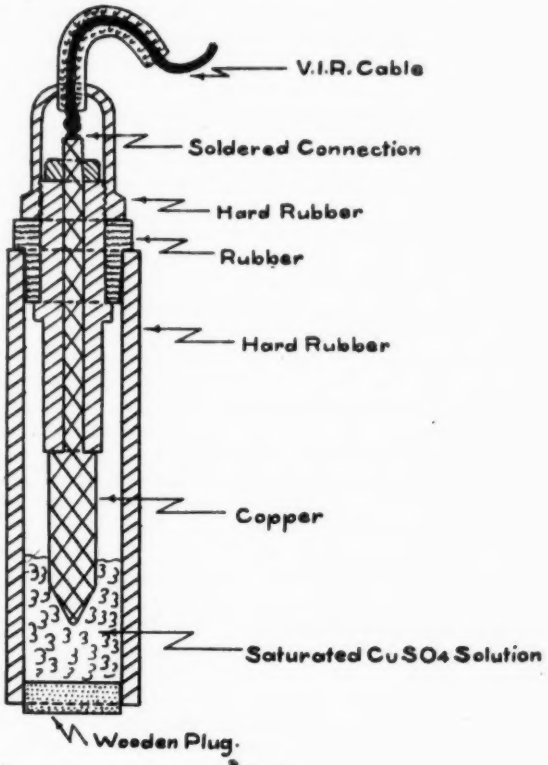


FIG. 4.

COPPER–COPPER SULPHATE ELECTRODE.

The construction of a copper–copper sulphate electrode for field work is of some interest. The type adopted in our work is shown in Fig. 4. This is

a sturdy reliable piece of field equipment which can be depended upon to give reproducible figures to the nearest 0·01 V. In working conditions certain precautions are necessary, such as that the copper itself is cleaned twice a day, that $CuSO_4$ crystals are present in the solution, that no copper sulphate or moisture is allowed to penetrate into the head of the cell, that no excessive contact potentials are set up at the ends of the leads by sweaty fingers, and so forth.

The figure of −0·8 derived in Fig. 3 as the solution potential of iron with reference to a Cu–$CuSO_4$ electrode is in close agreement with the usually quoted figure of −0·85 V, as a safe protective potential. It is generally accepted that an imposed potential of −0·85 V is sufficient to prevent the corrosion of a buried steel structure in the conditions commonly encountered in practice. It might well be considered that a criterion of such economic importance should be supported by reference to some specific investigation, in fact, it has been shown [2] that the correlation of potential and corrosion is not very readily established. Moreover, the translation of small-scale laboratory experiments on to the scale of a pipeline hundreds of miles long and running through many different soils is evidently a somewhat uncertain matter. Some writers [3] have stated that a break may be observed in the current density–potential curve at the point where protection is obtained. In practice, this method of determining the point at which a pipeline is fully protected is somewhat cumbersome to apply by comparison with the simple straightforward taking of pipe-to-soil potentials using a copper-sulphate electrode. In areas where the length of pipeline to be protected may run into hundreds of miles, the question of ease of application is of great importance in weighing the respective merits of differing criteria of protection. Over-protection is not usually very disadvantageous either technically or economically; under-protection is more serious.

In measuring potentials between the pipe and the ground, contact is made to the pipe either by digging or by means of a steel bar driven down to the pipe. The Cu–$CuSO_4$ electrode is then placed in contact with the soil surface over the pipe. In dry ground contact is assisted if a little water is used. It is important that the point of contact should be firm, consolidated ground. The presence of deep, dry dust will often prevent a trustworthy reading from being obtained. Several methods are available for the measurement of pipe-to-soil potential. A potentiometer circuit has been found to be the most generally satisfactory. The galvanometer used requires to be of a delicate type which at the same time is capable of standing up to field work and rough transport conditions. It has been found that a Cambridge pivoted-coil instrument gives excellent service, and a number of these have been built into circuits developed by the I.P.C. A valve voltmeter may be used with good effect, but is decidedly less portable than a potentiometer and is best mounted permanently in a vehicle with its battery. It suffers also from the defect of being decidedly slower in action than a potentiometer. Specially sensitive high-resistance galvanometers are now used in the United States for the purpose of directly measuring pipe-to-soil potentials. The exclusion of dust from the instrument is essential. The use of a null method for measuring potential is more important in the case of a line which does not carry an imposed potential. In this latter case the e.m.f.s involved are, of course, usually low and change

immediately if any appreciable current is drawn from the circuit. In surveying a line which is believed to be corroding, the existence of local variations in the pipe-to-soil potential along the line can give valuable indications of anodic areas [4] and in this work a quick-acting portable instrument is essential if much ground has to be covered.

The Application of Cathodic Protection.

In practice the application of cathodic protection requires a source of D.C. between the anode and the cathode to be protected. Fig. 1 shows diagrammatically a pipeline cathodically protected by means of a rectifier drawing 230 V A.C. from the mains supply and delivering low-voltage D.C. to the installation. The pipeline is connected to the negative of the source of current and the ground bed to the positive. Obviously, the ground bed or anode is constructed of the cheapest available material. Usually in oilfield areas a good deal of scrap pipe, old machinery, and such like may be obtained for this purpose. The proper design of a ground bed is an

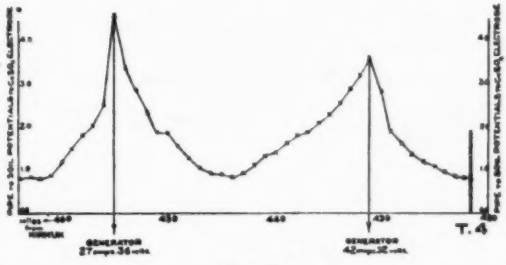


Fig. 5.

individual study in each case and is considered in more detail in a later section.

The practical question of applying cathodic protection to a particular structure resolves itself into a consideration of the most suitable and economical means of applying D.C. to it in such a manner as to secure a general difference of potential between the ground and the steel of not less than −0·85 V. At this point it is necessary to refer to the matter of pipe coating which is intimately connected with almost all aspects of cathodic protection. The specific topic of pipe coatings is discussed more fully in a later section; here we consider only the relationship between pipe coating and spread. In the case of pipelines, the economics of any system of cathodic protection are usually controlled and defined by the spread which may be obtained from a single ground bed, that is to say, the length of line which may be protected by a single installation. This factor of spread is largely dependent on the coating. The spread from a single installation may vary all the way from a few hundred yards in the case of a bare pipe immersed in seawater up to 50 or 70 miles in the case of a well-coated pipeline laid in ground of moderate or high resistance. Some typical illustrations of spread are contained in Figs. 5, 6, and 7, which represent the distance-potential diagrams of a number of different installations in the desert.

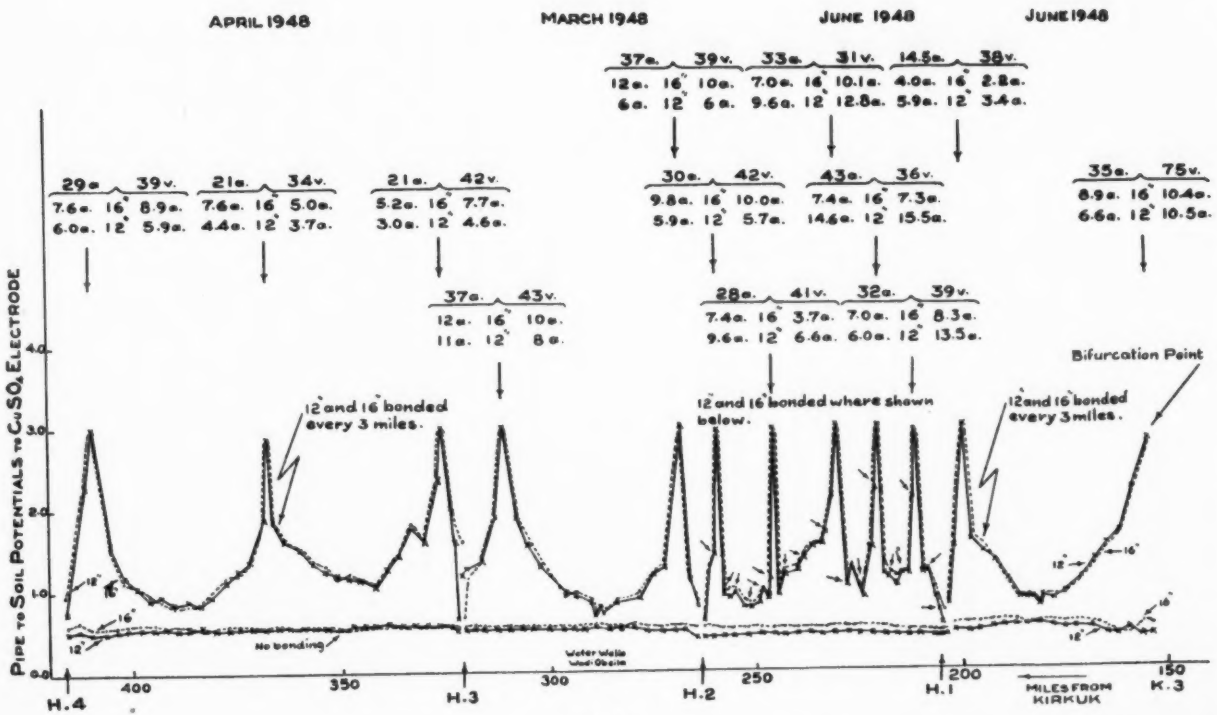


FIG. 6.

CATHODIC PROTECTION—CURRENT SURVEY.

It might be thought that the spread could be increased by the application of a greater current through the individual ground bed. This is true only within limits which are themselves set by other considerations. In the case of bare steel there is no definite limit to the maximum potential which may be used, although naturally the minimum effective potential and therefore current would be aimed at. However, with bare steel the spread which can be obtained is always very limited, and increasing the applied potential at the point of application merely wastes current at that point without improving the spread very much. With coated pipelines, however, the upper limit of potential at which it is safe to operate becomes a consideration. The evolution of hydrogen from a pipe surface commences at a potential of around 1·0 V, but appears not to become rapid below 2·5 V. In small amount the hydrogen diffuses away harmlessly, but there is an evident

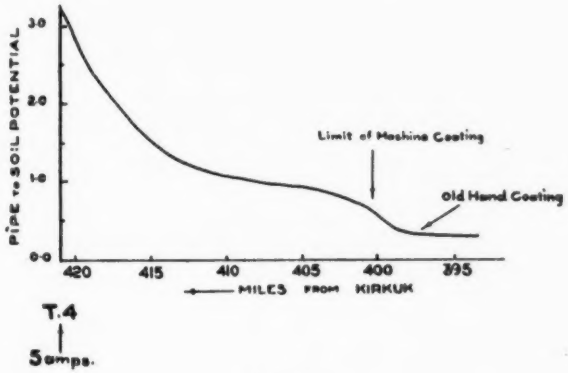


FIG. 7.

INSTALLATION AT T–4.

possibility of loosening the coating if gas is evolved on the pipe surface at too high a rate. In general, it is considered inadvisable to operate an installation on a coated line at a potential exceeding 3 V. This limitation is not as hampering in practice as might be imagined. The additional spread obtained by raising the pipe potential at the point of application of the current from 2 to 5 V is not usually very great even on a coated line. A sharp peak is generally found adjacent to the ground bed, and increasing the peak voltage does not usually result in lifting the potential-distance curve to a proportionate degree, this is seen illustrated in Figs. 5 and 6. Likewise the existence of lengths of poor coating will give rise to a sharp fall in the potential-distance diagram. Fig. 7 illustrates this condition. The line from mile 400 to mile 421 (T–4) is newly reconditioned with a good coating, whereas east of mile 400 the coating is somewhat poor. It is apparent from the form of the diagram that no practicable rise in potential at T–4 will have any appreciable effect at mile 395. In order to protect the pipeline at this point a local installation is essential.

The protective current density required by a particular pipeline is closely

related to the spread obtained from a single installation, since both are controlled by the coating resistance. A few typical examples may be quoted to show the wide range observed in practice. A 12-in line with the coating in only fair condition might be expected to give a spread of 5 to 7 miles on either side of the ground bed and to require an average of 2 or 3 amps/mile in ground of moderate resistance, that is to say, 2000–10,000 ohms/cm^3. The same line if coated by machine with a first-class pipeline enamel properly wrapped and carefully laid might very well give a spread of 25 to 40 miles on either side of the ground bed at a current consumption of less than 0·25 amp per mile. Within limits the spread obtainable from a single installation appears to be independent of the size of the pipe. Current consumption, of course, is proportional to the diameter of the pipe if the coatings are equally good. It is usually found that bare metal will require between 3 and 10 mA/sq. ft. in order to maintain a potential of −0·85 V between itself and the surrounding soil.

Supply of Current.

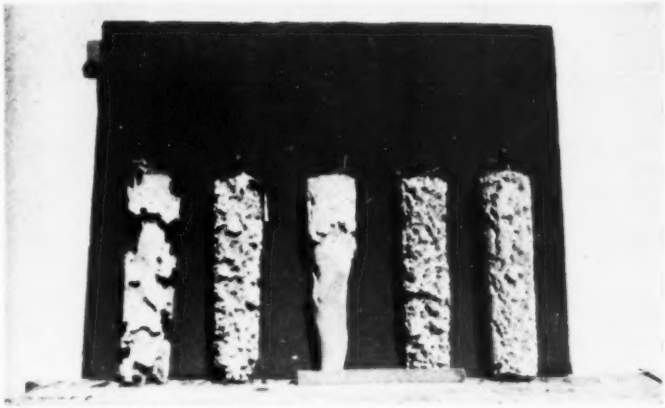
For all practical purposes sources of current are limited to the following :

1. Power line.
2. Generator sets powered by gas, oil, or petrol engines.
3. Galvanic anodes.
4. Wind generators.

The relative merits and fields of application of the foregoing sources of current may be considered individually.

Power Line.

Where an A.C. supply exists, as in a pump-station, the most satisfactory and economical method of obtaining low-voltage D.C. current for local-protection purposes is by means of a transformer–rectifier unit which obviates the use of moving parts and reduces maintenance to a minimum. The construction of a new A.C. power line specifically for the purpose of supplying current to protective installations is an expensive operation. The power take-off from such a line is usually small and considered purely as an electrical-supply undertaking could never be contemplated over the long distances often involved in pipeline practice. However, viewed from the angle of ensuring a continuous source of protective current, it can be justified in certain circumstances. Again, the all-important question of spread is the controlling factor. If the length of power line to be built exceeds 12 miles, then it can be shown that the use of isolated unattended diesel, gas, or petrol generating sets is probably a more economical proposition. In the case where the original source of power is a pump-station, and hence any new power line, would run parallel to the pipe, the case reduces itself in the first instance to the question of whether the spread from a single installation is as much as 6 miles either way. If the spread exceeds 6 miles, then a generator set is preferable on economic grounds. This observation, however, is conditioned by the amount of current which can be passed through a single ground bed. If this is limited, as it often is in desert areas, then the maximum throughput of the individual ground



Output, amp. hr.:	240	518	1944	517	200
Efficiency, %:	17	9	20	10	10

PLATE I.

MAGNESIUM 13 LB ANODES RECOVERED AFTER USE IN THE DESERT.

[*To face p.* 714.

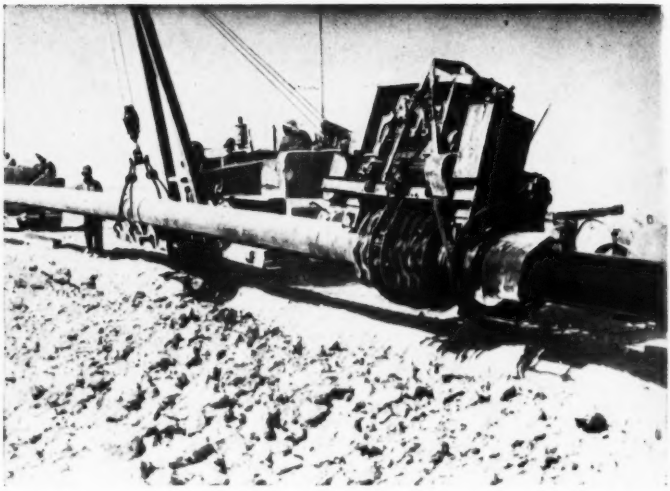


PLATE II.

THE SCRAPING AND PRIMING MACHINE IN MOTION TOWARDS THE LEFT. THE PRIMING HEAD IS ON THE RIGHT.

PLATE III.

THE COATING AND WRAPPING MACHINE AT REST.

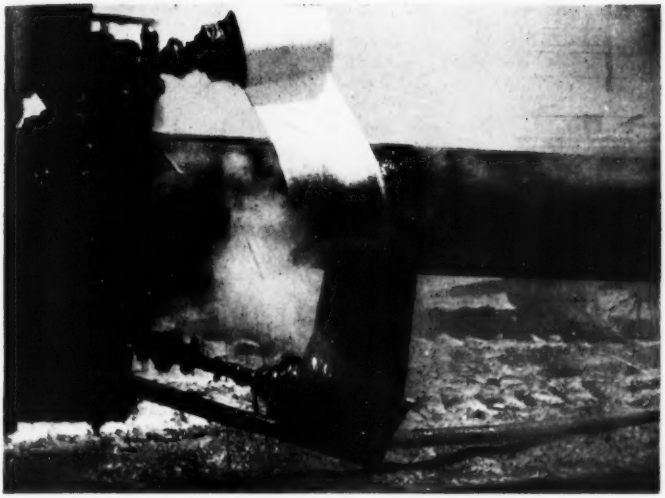


PLATE IV.

THE COATING AND WRAPPING MACHINE IN MOTION USING COAL TAR ENAMEL, FIBRE-GLASS, AND RUBEROID. THE HOT ENAMEL IS DRAWN FROM THE MELTING POT THROUGH THE FLEXIBLE METAL HOSE SEEN ON THE GROUND.

PLATE V.

TESTING THE PIPE COATING. THIS TYPE OF ELECTRONIC DETECTOR IS PORTABLE AND SELF-CONTAINED, RUNNING ON RUBBER WHEELS ALONG THE PIPE AND PUSHING THE ROLLING COIL SPRING ELECTRODE BEFORE IT.

PLATE VI.

CURRENT SURVEY. ESTABLISHING A CAMP.

PLATE VII.

CURRENT SURVEY. CONTACT WITH THE PIPE WAS OBTAINED BY MEANS OF A C CLAMP.

bed may be the limiting factor in spacing installations. The existence of D.C. supply is not so favourable owing to the increased difficulty of voltage change. Usually the ground bed applied voltage will not exceed 50 V and may be as low as 5 V, depending on the ground-bed resistance and current required. The use of D.C. supply involves motor-generator sets to transform standard voltage to the low-voltage high-amperage type of power required. These sets are quite satisfactory if they can be mounted in a position where they will receive adequate maintenance. For long-distance transmission, of course, such as is required on a pipeline, D.C. is less suitable on account of the increased difficulty of transforming H.T. power to low-voltage supply.

Generator Sets.

In the United States, natural-gas pipelines are frequently protected by means of gas-engined generator sets. These operate in isolated locations along the right-of-way and are visited only at intervals of say a week by an inspector. These gas engines, of course, draw their fuel direct from the line through a reducing valve.

On oil pipelines, the choice is between petrol and diesel generators. The economics of using such units is governed by the question of whether they can be left to run unattended for considerable periods between the visits of an inspector. This is particularly true of uninhabited areas such as the deserts of the Middle East, where the establishment of attendants for such a unit would involve quarters, watchmen, rations, water, and other services to be supplied to some isolated spot. With proper arrangements it is quite possible for such units to be run unattended save for occasional visits by an inspector. Diesel units have been supplied for use on aircraft beacons which are visited once monthly only. It is evident that such an arrangement calls for a specialized type of machine equipped with adequate fuel, lubricating oil, and water storage, and provided with a system of shutdown devices to obviate damage in the event of failure of some essential part.

Galvanic Anodes.

The use of galvanic anodes for the cathodic protection of pipelines, tank bottoms, and internally of water tanks, has assumed considerable importance of recent years. It is evident that for this purpose an anode must at the same time be electro-positive to iron and reasonably cheap. Self-corrosion of the anode should also be low. An inspection of the electrochemical series, Table I, shows that for all practical purposes the choice is limited to magnesium, aluminium, and zinc.

Table II lists the performance of the various metals as galvanic anodes, viz :—

1. Nominal e.m.f. to iron.
2. Open circuit potential difference to iron obtainable in practice.
3. Open circuit potential difference to iron when pipe-to-soil potential is −0·85 V.
4. Electrochemical equivalent in amp hr/lb.

TABLE II.

Metal.	Nominal e.m.f. in conjunction with iron.	Commonly observed e.m.f. in conjunction with iron in soil.	Available p/d. in protective circuit with iron at −0·85 V.	Nominal amp hr/lb.
Magnesium .	2·0 V	approximately 1·2 V	approximately 0·8 V	1,000
Aluminium .	1·3	0·5	0·1	1,350
Zinc . .	0·3	0·3	nil	370
Iron (Ferrous) .	—	—	—	435

It should be noted that the nominal e.m.f. of the cell is not always available in practice. Usually, a magnesium anode when first connected to a pipe will show an open-circuit voltage of around 1·2 V, which is reduced to around 0·7 V, as the pipe-to-soil potential is brought up to −0·9 V. Likewise the nominal electrochemical equivalent of an anode is not realizable in full. Magnesium usually undergoes a good deal of unprofitable self-corrosion; an overall efficiency of 50 per cent may be regarded as indicating a satisfactory installation in most types of soil. In most soils the e.m.f. generated by zinc is too low to be completely effective. When zinc is used as a sacrificial anode in connexion with steel pipe it is usually found that the available e.m.f. is insufficient to raise the potential of the pipe above −0·7, whilst at that figure the potential difference and therefore current output obtained is almost negligible, and accordingly the length of line which can be protected with a single anode is rather small.

Magnesium can be described as being very useful for cathodic protection in suitable conditions, that is to say :—

1. Current requirements should be less than 1 amp/mile of pipeline if long lengths are involved.
2. The ground should be of a resistivity not exceeding 1000 ohm/cm³ and preferably below that figure.
3. The ground should not dry out in summer to such an extent as to raise the resistivity much above 1000 ohms.
4. A good, strong clay having some base-exchange properties is an excellent location for magnesium.
5. In marine installations magnesium may be used with good effect and will then give considerable current outputs.
6. In isolated corrosive marshes remote from other power supply, magnesium is particularly useful.

In ground with a resistivity of around 1000 ohms/cm³, a 13-lb magnesium anode may be expected to give an output of around 0·1 amp when connected to a pipeline which is itself at a potential of −0·9 V to a copper-sulphate electrode. Galvanic anodes vary in output dependent on the soil resistivity, and consequently in climates where rainfall is restricted to a particular season, a distinct falling off in current output is observed as the dry season progresses. In addition, galvanic anodes tend to show a progressive decline in output with age. In desert locations in the Middle East, magnesium has proved disappointing on account of the generally high

resistivity and arid state of the ground. Our experience with magnesium is described in more detail in a later section.

It has frequently been suggested that galvanic anodes possess some special virtue whereby they are able to afford protection to a pipeline at a lower potential than is usually employed in the case of an imposed current. This claim does not appear to the writer to possess any particular experimental justification, and meanwhile must be treated with reserve.

In the section on ground beds it is noted that the resistance between a buried conductor and the earth is an inverse function of its length. It is evident therefore that by increasing the length of a galvanic anode, a lower circuit resistance, and consequently a greater output, may be obtained, since the e.m.f. of the cell itself is fixed by the electrode potentials of the metals concerned. This principle is being utilized, and magnesium in the form of a ribbon of approximately 0·5 sq. in. cross-section is now available from magnesium manufacturers both in the U.S.A. and the U.K. Continuity is ensured by fabricating the ribbon round a core of stranded steel wire.

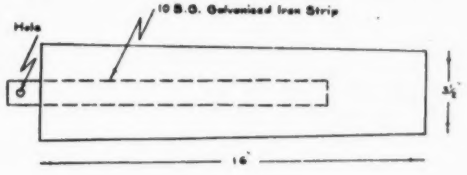


FIG. 8.

13-LB CONE ANODE WITH GALVANIZED STRIP CONNEXION.

The chemical composition of the metal is important, since it has considerable bearing on the self corrosion of the anode and therefore its efficiency as a source of current. The analysis specified by the leading manufacturer [5] of magnesium in the United States is :—

Aluminium	5·3 to 6·7 per cent
Manganese, minimum	0·15
Zinc	2·5to 3·5
Silicon, maximum	0·3
Copper, maximum	0·05
Nickel, maximum	0·003
Iron, maximum	0·003
Other impurities, maximum	0·3
Magnesium	Remainder

The backfill employed is of importance, it should contain a large proportion (75 per cent) of gypsum mixed with a good, strong water-retaining clay. The mix should not form cavities on drying out. The efficiencies observed in actual installations in the Middle East vary from 3 to 80 per cent. In desert locations outputs are usually very low, and efficiencies erratic but mainly very low. In the coastal areas where well-developed clays of low resistivity are encountered, efficiencies tend to run from 30 to 50 per cent. In general, 40 to 50 per cent may be regarded as a satisfactory figure. Some examples of anodes recovered after use in the desert are shown in Plate I.

The form of attachment of the lead to the anode is of interest. The type of connexion found most satisfactory is shown in Fig. 8. The insertion of

a galvanized-iron strip into the anode ensures continuity, and at the same time permits a connexion by soldering or bolting as may be desired. Subsequently, the top of the anode and the protruding insert are coated with asphalt to obviate corrosion at the junction of the lead and galvanized iron.

Wind Generators.

Wind generators have numerous disadvantages of which the intermittent nature of the current supplied is not the least. It is quite generally considered now that a current flowing for less than 80 per cent of the whole time is not merely wasted but positively detrimental. Wind machines had a considerable vogue in the U.S.A. formerly and are still being erected in suitable locations. Their design is specialized and is only now becoming reasonably satisfactory. In view of their elevated position proper inspection and maintenance of wind generators is quite a problem, and in general, there can be little doubt that this method of generating current leaves much to be desired. However, in isolated non-corrosive atmospheres where a steady breeze is assured, they may be usefully employed.

Ground Beds.

Any non-ionic conducting material may be used to form the anode or ground bed. In practice this confines the choice to such cheap and readily available substances as scrap iron and carbon in the form of graphite or coal coke. The consumption of iron in such an anode is approximately 20 lb/amp year, that of coke is very much less, reflecting the lower equivalent of carbon compared with iron. The reaction is essentially the same : in each case discharge of [OH] ions with oxidation of the anode. Evidently this process must result in a progressive loss of water in the vicinity of the ground bed.

$$2\,[OH]' + 2\,e^+ \longrightarrow H_2O + \tfrac{1}{2}O_2$$

$$H_2O \rightleftharpoons [OH]' + H^+$$

$$Fe + \tfrac{1}{2}O_2 \longrightarrow FeO$$

$$C + O_2 \longrightarrow CO_2$$

Cast-iron anodes soon develop a resistant coating of graphite on the surface. Likewise, the application of caustic soda to the scrap results in a passivated surface on the iron from which gaseous oxygen is evolved, this again reduces the consumption of metal. Where coke is used coal coke is essential, petroleum coke being non-conducting. A soil pressure of at least 40 lb sq. ft. is required. Graphite rods are very resistant to oxidation and show little deterioration even in seawater.

In desert areas the most important characteristic of an anode is its resistance—that is to say, the resistance between ground bed and pipe. The total external resistance of the whole circuit may be broken down into components as shown in Fig. 1, where we have :—

R1 = Resistance of D.C. supply line between pipe and ground bed.
R2 = Contact resistance between ground bed and soil.
R3 = Resistance of earth path.
R4 = Resistance of pipe coating.
R5 = Resistance of pipe.

Considering the foregoing components it is evident that R1 can be made as small as is desired, whilst R4 is fixed and the higher the better. R5 is also fixed but small. The resistance R4 of the coating is a most important factor in any scheme of cathodic protection. The potential between soil and pipe is little more or less than the volt drop across the pipe coating, and the object of the whole arrangement is to maintain this volt drop at a figure of −0·85 V or more :—

$$E = I.\mathrm{R4}$$

Evidently as the coating resistance R4 increases so does the value of the required current I diminish. In any particular instance the coating resistance is established; it naturally varies somewhat with the amount of moisture present in the ground, but at any particular time it is invariable. Evidently, then, the condition of the coating controls the amount of current required to maintain a protective potential on a given line, that is to say, the current requirements of a circuit are irrespective of the remaining resistances in the circuit R1, R2, R3, and R5. As previously stated, R1 the conductor resistance may be varied at will within wide limits to suit the circumstances of the case. Thus it appears that R2 and R3 are the principal uncontrolled variables in the total resistance of the circuit, and it becomes a matter of importance to ensure that they are at a minimum, since the energy consumption of the circuit is proportional to its total resistance. The individual values of R2 and R3 are difficult to determine, but both are affected by the same factors of which anode form, soil resistivity, and water content are the chief.

The selection of a suitable site for a ground bed is a study in each individual instance. This is more particularly so in the case of a pipeline as distinct from a pump-station or tank farm, since the possibilities as to precise location are more restricted in this latter instance. On a pipeline with a spread of 10 or 20 miles either way from a cathodic-protection installation the position of the unit may be varied within limits of perhaps 2 or 3 miles without serious detriment. In desert areas, such as those of Iraq and Syria, considerable exploratory work may be required in order to identify a suitable site of low resistivity. In most of the high desert the subsoil consists of rock which usually occurs not more than 2 or 3 ft below the surface. The winter rainfall runs from 3 to 6 in only, and soil resistivities are high; accordingly the location of ground beds is often a matter of some difficulty. To a considerable extent a site of high resistivity may be offset by utilizing a ground bed of greater length. The shallow soil necessitates anodes being laid horizontally and at small depth. The most favourable depth will be indicated by soil-resistivity measurements taken either with Shepard Canes or by the four-electrode method, or even quite simply by driving steel bars into the ground, applying a battery potential, and observing the current flow.

The passage of a current from a small anode in the earth produces ideally a series of spherical surfaces of equipotential. It follows from this that in cases where the soil resistivity is high, length rather than superficial area is the desirable feature of an anode, or going farther, that a discontinuous colinear series of anodes is an even more effective method of utilizing a given weight of metal. Fig. 9 shows the effect on the resistance to ground of

increasing the length and cross-section of the anode in three typical soils. The curves are calculated for soils of resistivity 1000, 4000, and 8000 ohms/cm³ respectively. Each pair of curves represents anodes of circumference 2 in and 75 in respectively. The small effect of increasing the extent of contact in the transverse section of the anode is strikingly illus-

LEGEND,
Soil Resistivity = 8000 Ohms/cm cube.
" " = 4,000 " " "
" " = 1,000 " " "
NOTE.
Calculated from Prof. Dwight's formula for horizontal ground bed
R = Resistance to earth.
ρ = Specific resistivity ohms cm cube of soil.
2L = Length cms. of anode.
S/2 = Depth cms. = 90 cms = 3 feet in cases shown.
a = Radius cms. of anode.
Anode diameter 0.8 ins.
Anode diameter 24 ins.
RESISTANCE TO GROUND OHMS.
LENGTH OF GROUND BED - FEET.
1,000
2,000
3,000

FIG. 9.

EFFECT OF LENGTH AND DIAMETER ON GROUND BED RESISTANCE.

trated. The curves in question have been calculated using Professor Dwight's formula for a horizontally buried conductor, viz :—

$$R = \frac{\rho}{4\pi L}\left(\log_e \frac{4L}{a} + \log_e \frac{4L}{s} - 2 + \frac{s}{2L} - \frac{s^2}{16L^2} + \frac{s^4}{512L^4} \cdots\cdots\right)^6$$

The resistance of the soil in the vicinity of a ground bed may be lowered by surface works designed to collect rainwater and direct it to the anode. In dry areas the possibility of directing run-off from neighbouring slopes to the ground bed is an important consideration in locating a site. The combination of bunding, dry drains, and such-like devices to direct water to the anode are particularly necessary in arid country, where water evaporated

or decomposed at the anode is hard to replace. The presence of water is essential to the proper functioning of an anode. The drying out of a ground bed can only lead to a progressive rise in resistance, a most undesirable condition.

Of course, in ground of low resistance, such as water-logged marshes, or in the extreme case marine installations, massive anodes such as scrap bed-plates, mud-pumps, draw-works, and such-like objects form satisfactory anodes. Contrariwise, in arid ground of high resistivity it may be found necessary to construct a ground bed totalling up to 500 or 700 yd in order to obtain a circuit of a sufficiently low resistance. In such cases only small cross-sections are required.

The overall resistance between ground bed and pipe, $R2 + R3 + R4 + R5$, should not exceed 0·5 ohms. This figure is frequently difficult to obtain in desert areas, and it may prove advantageous or necessary to haul water to the ground beds in summer. The resistance of the ground in the immediate vicinity of the anode may be improved to some extent by the addition of gypsum, clay, or other water-retaining substances.

Pipe Coatings.

The object of coating a pipe is, of course, to improve its resistance to corrosion. Corrosion may be prevented by either one of two means; first, the pipe surface may be completely insulated electrically from contact with soil moisture; or secondly, the action of the soil moisture may be brought to a standstill by the use of cathodic protection. In practice, no existing pipe coating is so impervious to moisture, in the conditions in which it is used, as completely to insulate the pipe. On the other hand, cathodic protection, whilst technically feasible in the case of bare pipe, nevertheless involves relatively heavy currents in order to maintain a protective potential. Current opinion is in favour of applying the best possible pipe coating which can be obtained without recourse to any extraordinary measures or unusually expensive materials. Subsequently, this coating is supplemented by cathodic protection, which is thereby rendered easy and inexpensive to apply and maintain.[7]

On the Iraq pipeline a distance of some 400 to 500 miles separates the rail-heads, Baiji in the east, Homs or Mafraq in the west, respectively. Pipe stringing over the intervening desert involves long hauls over rough country. In these circumstances it has always been considered preferable to coat the pipe over the ditch rather than establish plants for shop coating at the rail-heads. Even in the U.S.A. over-the-ditch coating is still probably the commonest method in use, and if carefully carried out is not inferior to shop coating. The initial preparation of the pipe is important. The use of phosphate-pickled pipe undoubtedly provides a good base for the subsequent coating, and if it can be obtained at low cost its use is well worth while. Alternatively, if acid cleaning is not used, the welded pipe should be thoroughly scraped and brushed over the ditch by two passes of the cleaning machine. On the second pass the cleaning machine primes the pipe. The subsequent application of a flood-coat of hot enamel after the primer has dried is now standard practice. The same machine that coats the pipe carries a rotating head by which any desired reinforcement or fabric covering

may be wrapped on to the pipe. Modern practice utilizes both a reinforcement and an outer wrapping. The reinforcement comprises an open-mesh glass tissue, which is wrapped into the hot enamel before the flood-coat has time to set. The still-liquid enamel forces its way through the fibre-glass forming a continuous film on the outside. The glass mat thus fulfils a function similar to that of the reinforcing in concrete. The same machine simultaneously adds a final outer wrapping of asbestos felt impregnated with asphalt, the purpose of which is to protect the enamel from soil stresses. The final cross-section of the coated pipe then appears somewhat as in Fig. 10. Plates II, III, IV, and V illustrate the processes of pipe cleaning, priming, coating, wrapping, and testing.

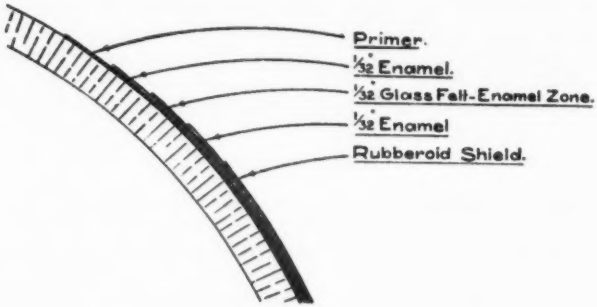


FIG. 10.

COMPLETE PIPE COATING.

Modern practice calls for the use of some form of electrical inspection of the pipe coating. This is usually carried out by running a rolling-spring electrode over the surface of the coating. The electrode is connected to a portable high-tension supply. The other terminal of the supply is connected to a trailing wire in contact with the ground. Usually this is sufficient to give a connexion with the pipe metal which normally will be in contact with the earth at some point. The coating is thereby subjected to a high potential difference. Where holidays exist an audible and visible spark occurs. Such places are of course marked and made good immediately.

THE APPLICATION OF CATHODIC PROTECTION TO THE IRAQ PIPELINES.

The two original 12-in lines were laid in 1933 and 1934, the south line from Kirkuk to Haifa and the north line from Kirkuk to Tripoli. At the time of laying, these lines were coated with asphalt enamel and wrapped with asbestos paper, these two operations being carried out exclusively by hand. From 1940 onwards, leaks became progressively more frequent, and by the end of 1947 more than 7000 had been recorded. In 1945 the company decided to undertake an extensive reconditioning programme with the object of putting the existing line in first-rate condition. Simultaneously, a Corrosion Engineering Department was established to study and recommend measures to obviate corrosion for the future on both the existing lines and those which it was proposed to build.

At this point it is convenient to consider a short description of the territory crossed by the trans-desert pipelines. Geographically, the oil field of Kirkuk is situated on the north-eastern edge of the Arabian Desert. The seasonal rainfall at Kirkuk averages around 16 in, but falls off very

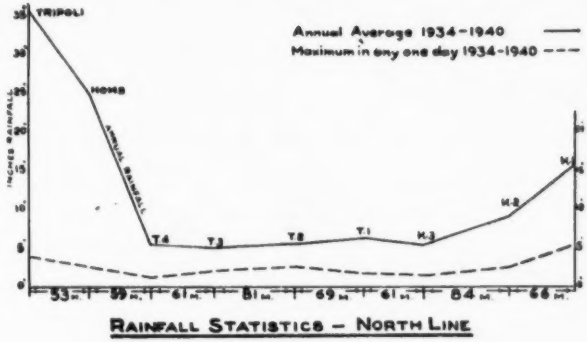


FIG. 11.

rapidly to the west as the desert is entered. At K–2, the second pumping station, desert conditions are encountered and persist on the north line for some 400 miles to the vicinity of Homs, which is itself in the fertile coastal belt of high rainfall. Similarly, on the south line fertile ground is again encountered in the hill country of Transjordan. Reference to the rainfall

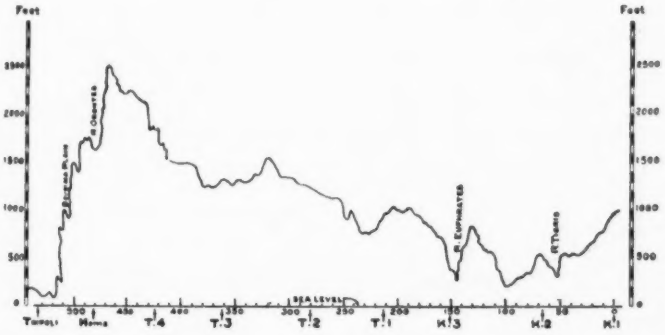


FIG. 12.

PROFILE DIAGRAM, NORTH LINE.

statistics, profile, and map, Figs. 11 and 12 (Kirkuk–Tripoli), and Fig. 13 will possibly aid in making the general picture more clear.

In the Middle East rainfall and drainage are found to play a decisive part in determining the corrosivity of the soil. Where the rainfall is sufficient to wash soluble salts deep into the ground, corrosion tends to be strictly local in character. In such areas, hollows, marshes, and irrigated fields

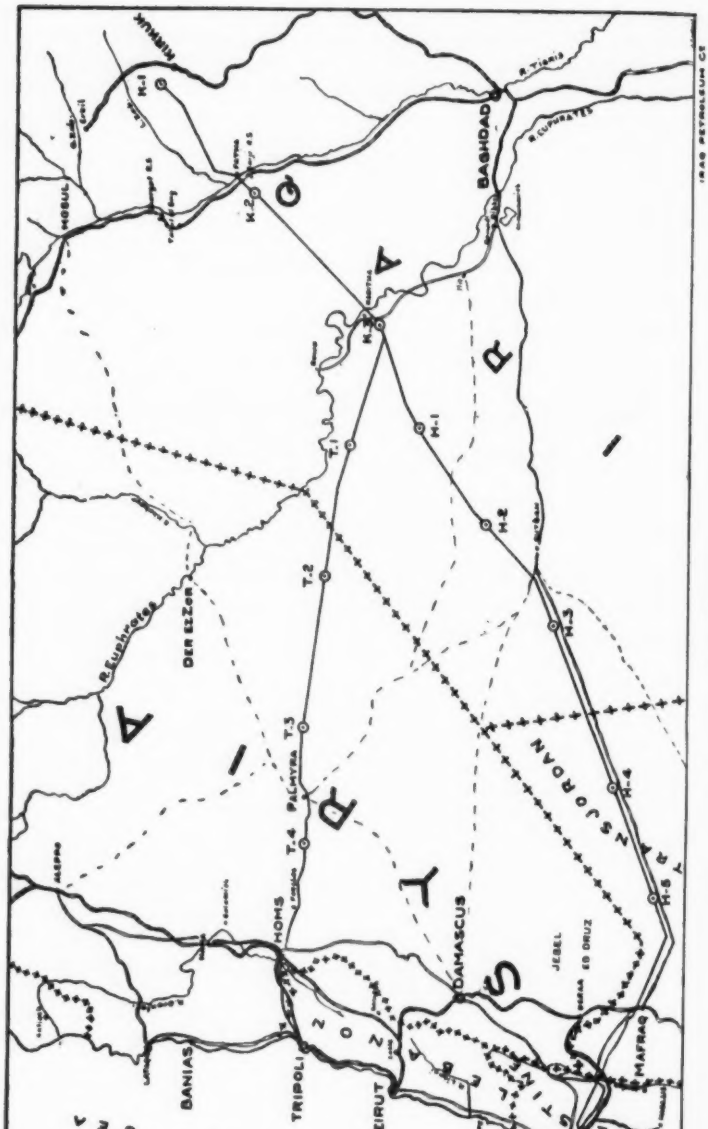

MEDITERRANEAN SEA
SYRIA
IRAQ
BANIAS
TRIPOLI
BEIRUT
HOMS
PALMYRA
DAMASCUS
HAIFA
MAFRAQ
DER EZZOR
BAGHDAD
MOSUL
KIRKUK
R. EUPHRATES
R. TIGRIS
JEBEL ED DRUZ
ZONE A
ZONE B
K-1
K-2
K-3
T-1
T-2
T-3
T-4
T-5
H-1
H-2
H-3
H-4
H-5

FIG. 13.

provide the most corrosive conditions. In these climatic conditions the soil where present is invariably fertile. In general, it may be said that a well-drained field of corn is unlikely to trouble the pipeliner very seriously with corrosion. In desert areas of rainfall below 8 in the soil is not leached by the winter rain. On the contrary, the effect of the infrequent but usually heavy storms is to concentrate those soluble salts already present in the soil into restricted areas. These concentrations, of course, give rise to salty patches when the ground dries out. Salty patches are to be found scattered haphazardly throughout the desert country of Iraq, Syria, and Transjordan. Their extent varies from a few inches to a few yards, or in the extreme case of closed basins, salt lakes or marshes several miles across may be formed. Throughout the high, gravelly desert these small patches are of frequent occurrence. Their presence may often be detected by eye and confirmed by tests with Shepard Canes or otherwise. They contain the chlorides and sulphates of sodium, magnesium, and calcium; in addition, nitrates are sometimes present. These patches are deliquescent and retain some moisture even when the surrounding soil has dried out. This in effect means not only that the desert ground is heterogeneous as regards salt content, but also that the oxygen content of the ground varies locally, the salts and retained moisture having a sealing effect.

The pipelines are buried throughout their length, and the backfill after fifteen years still remains distinctly softer than the surrounding ground, with the result that the ditch acts as a sink and collector for soluble salts which are washed down into it during the rainy season. This no doubt is an additional source of trouble.

Experience has demonstrated that the greater part of this desert country is corrosive. The exposure of the line during the execution of the reconditioning programme showed that over long distances hardly a single mile of pipe was free from attack. The most corrosive conditions of all are found not in salt flats and basins where the ground is fairly uniformly laden with salt. Rather it appears that an open-textured sandy loam containing scattered salt patches constitutes the most active soil. In such country the run of ground will show resistivities of 5000 to 10,000 ohms/cm^3; scattered deliquescent salt patches run from 500 to 2000. It is noticeable that marls containing much gypsum tend to be distinctly less corrosive than the more open sandy soils mentioned above although salt patches occur as frequently in the former as in the latter. The effect of rain in gypsum country seems to have a sealing action on the soil, which doubtless reduces the oxygen content of the ground.

In the coastal areas of high winter rainfall, very different conditions obtain, and in general, corrosion is confined to certain well-defined areas where swampy conditions prevail. Bacterial corrosion has been suspected in such areas, but remains unproved.

In considering the problem of applying cathodic protection to the Iraq pipelines, one of the first possibilities to be investigated was the use of galvanic anodes, about which at that time very little was known outside of the U.S.A. In the isolated and uninhabited areas with which we are concerned the provision of electric power for cathodic protection over the major part of a right-of-way totalling 1150 miles, represents a substantial undertaking. It was hoped that the use of magnesium as a sacrificial anode

might enable us to avoid the use of generated power for cathodic protection. Several hundreds of magnesium anodes and a smaller number of zinc were obtained and installed in various typical locations along the pipeline. Observations were made at frequent intervals to determine the current output of each anode. Efficiency figures were obtained by noting the weight loss at the end of the test period and comparing the calculated theoretical output with that observed. The actual installation of the magnesium proved a matter of some difficulty at many points. In the desert generally the depth of soil seldom exceeds 3 ft and may be very much less. Nevertheless, corrosion is encountered in these shallow soils, and to be effective a system of protection must be capable of application at all such points. Frequently some searching was necessary in order to discover a sufficient depth of ground to provide a few inches of cover to the anode. Various different backfills were experimented with, and on the whole gypsum–clay or gypsum–bentonite mixtures appear as good as any. In the desert areas generally galvanic anodes were not a success; the current output obtained from a single anode was usually very low running from 5 to 30 mA. Occasionally an anode located actually in a salt patch would give out as much as 250 mA. The output of adjacent anodes was very erratic and this involved a great deal of experimental work to each installation. This of course increased the cost greatly. The current requirements of the pipeline which have to be protected are of the order of 1 to 3 amp/mile, it therefore became evident that the number of magnesium anodes which would be required was impracticable for large-scale application. It should be mentioned that within limits, size of anode had but little effect on output, on the average the output of a 13-lb anode differed little from that of a 45-lb anode. Similarly, differing backfills had little effect on output. At that time magnesium ribbon was not available for test purposes.

Successful installations with magnesium have been effected in the coastal areas of Palestine and Syria. The pipeline route mid-way between Homs and the coast passes across the Bouqaia Plain, a filled valley with steep sides and a level floor. The soil is a heavy, strong clay derived from the lava-strewn hills surrounding the plain. This soil is exceedingly rich, and the valley, which is watered by several perennial streams, is subject to irrigation during most periods of the year, rice, lentils, and maize being grown extensively. Owing to the soft, wet nature of the ground and the numerous water channels, access to this portion of the right-of-way is a matter of some difficulty for wheeled vehicles or equipment at all times of the year, whilst in the rainy season the plain takes on the character of a marsh. In the autumn of 1947 several severe leaks in the plain pointed to the urgency of applying cathodic protection. The Bouqaia is some 30 miles from the nearest source of electric power, and in view of the favourable nature of the ground it was decided to protect the 3 miles of pipe lying in the marsh by means of magnesium. In the first instance some ten or twelve anodes were installed at intervals of 200 ft. Pipe-to-soil potentials were taken from which it appeared that the current supply was insufficient to raise the pipe to −0·85 V. Accordingly, the spacing was reduced, and in all 151 magnesium anodes were installed in a total distance of around 3 miles. In this area the soil is deep, and no difficulty was experienced in drilling an 8-in hole to a depth of 5–8 ft by means of hand augers. Insofar

as supplies permitted a gypsum–clay mixture was used as backfill. Each anode was situated approximately 10 ft from the pipe, which at this point is a 12-in line, most of which has not been recoated since it was originally laid in 1933. The current output of the various anodes was observed at the time of connexion, and on the average amounted to 60 mA. Individual anodes gave readings between 30 and 150 mA. Subsequently, a survey showed that pipe-to-soil potentials ranged between −0·9 and −1·1 V at all points lying in the marsh. Owing to the nature of the area it was not possible to leave the connecting leads open, so that a record of current output has not been obtained. However, subsequent to the installation no further leaks have been observed, and a survey at the expiration of 12 months showed that the pipe-to-soil potentials had hardly changed. Fig. 14 shows graphically the potentials obtained. It will be observed that the current requirement of the 12-in line in this low-resistance soil is around 3 amp per mile. It was at one time suspected that corrosion in this area might have its origin in sulphate-reducing bacteria, but specimens of clay taken from the vicinity of the pipeline have failed to develop H_2S in Baars' culture solution.

Cathodic Current Survey.

Simultaneously with trials of galvanic anodes a survey was carried out over the greater part of the pipeline right-of-way to determine two indispensable facts on which any scheme of cathodic protection would have to be based.

1. The amount of current required to maintain each section of the line at a protective potential.
2. The spread which could be obtained from a single installation in the same section.

The apparatus used for the survey comprised three 1·75-kW Lister diesel generating sets rated at 32 V, 55 amps. These sets were each mounted on a 3-ton covered trailer.

The mode of operation adopted was essentially simple. In the section which it was desired to test a suitable site was chosen for a ground bed. One generator was then towed to the pipeline opposite the spot in question and a small camp for attendants and watchmen set up. A temporary ground bed was established utilizing short lengths of 2-in pipe set vertically in the ground. A hole was augered as deeply as possible, which was usually between 2 and 3 ft and the pipe set in and well watered to ensure good contact. The number of such pipes required at a single installation varied between thirty and eighty connected in parallel. After considerable experimentation effective geometric patterns were discovered. A connecting cable would be run across the surface of the ground to the generators. Usually, of course, the ground would be dry and the neighbourhood sparsely inhabited, so no difficulty was experienced with the use of bare cable. The ground bed would thus be connected to the positive of the generator, and the pipe to the negative. Where multiple pipelines exist, bonding was required at intervals such that a uniform pipe-to-soil potential gradient was observed on each line.

Whilst the installation was being established (Plates VI and VII), a

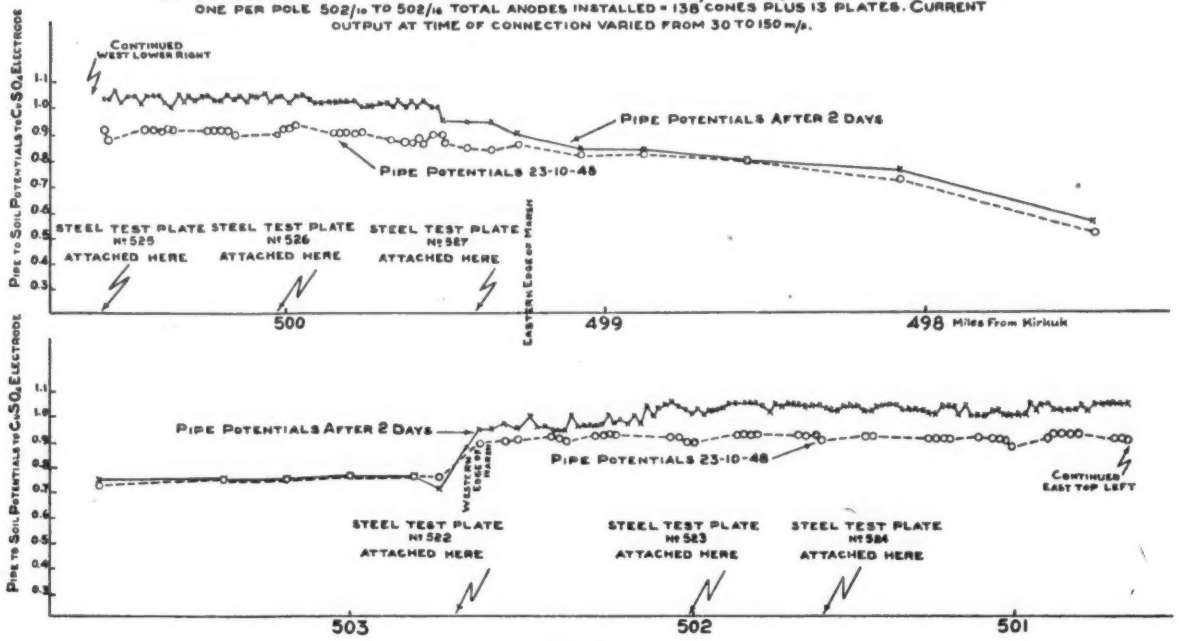

CONE ANODES INSTALLED AT RATE OF TWO PER POLE FROM 499/13 TO 502/9 PLATE ANODES INSTALLED ONE PER POLE 502/10 TO 502/16 TOTAL ANODES INSTALLED = 138 CONES PLUS 13 PLATES. CURRENT OUTPUT AT TIME OF CONNECTION VARIED FROM 30 TO 150 m/a.
CONTINUED WEST LOWER RIGHT
PIPE POTENTIALS AFTER 2 DAYS
PIPE POTENTIALS 23-10-48
PIPE TO SOIL POTENTIALS TO Cu-SO4 ELECTRODE
STEEL TEST PLATE Nº 525 ATTACHED HERE
STEEL TEST PLATE Nº 526 ATTACHED HERE
STEEL TEST PLATE Nº 527 ATTACHED HERE
EASTERN EDGE OF MARSH
500
499
498 Miles From Kirkuk
PIPE POTENTIALS AFTER 2 DAYS
PIPE POTENTIALS 23-10-48
CONTINUED EAST TOP LEFT
STEEL TEST PLATE Nº 522 ATTACHED HERE
STEEL TEST PLATE Nº 523 ATTACHED HERE
STEEL TEST PLATE Nº 524 ATTACHED HERE
503
502
501

Fig. 14.

MAGNESIUM INSTALLATION IN BOUQAIA PLAIN, MILE 499/13 TO 502/16 NORTH. INSTALLED NOVEMBER 1947.

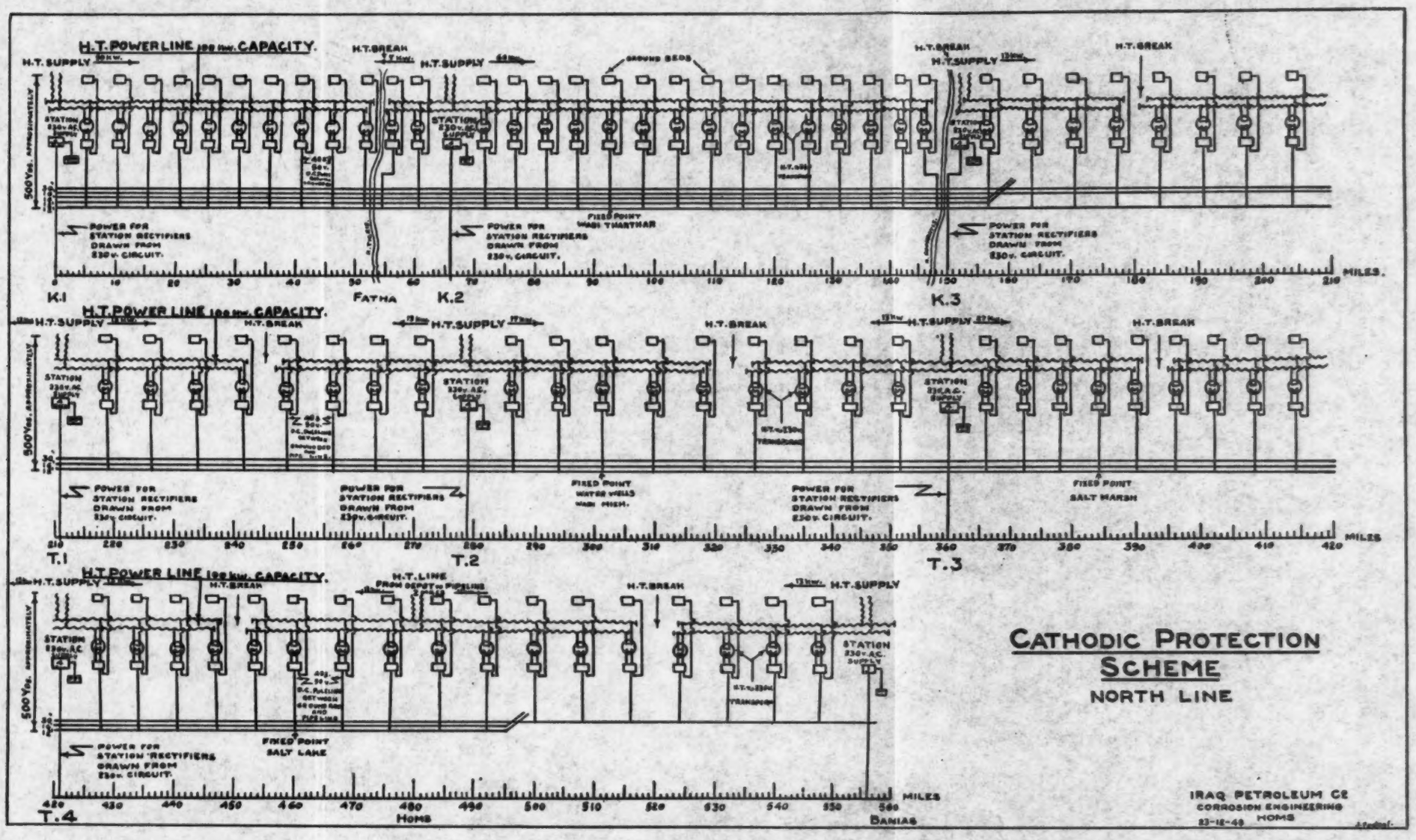


FIG. 15.

[To face p. 733.

matter of some days, another party would be at work digging holes down to the line and taking pipe-to-soil potentials at suitable intervals. Usually these potentials show little variation over considerable distances prior to application of current. The generator would now be started up, and the applied voltage adjusted by means of a rheostat in the field windings until sufficient current flowed between the ground bed and the pipeline to raise the pipe-to-soil potential at the point of application to 3 V. Frequently, the resistance of the first ground bed would prove too high to enable this to be done with the available voltage in hand. In specifying future generators for this purpose we should adopt a higher figure than 32 V. The generator would be run for some hours until steady conditions had appeared. The line party would then repeat their series of pipe-to-soil potential readings in either direction from the installation until the point at which the effect of the ground bed faded out could be ascertained.

A second generator could now be sited to the west of the first at a distance rather more than double the length originally covered, that is to say, the fade-out point would be rather less than half-way between the first and second generators. The fade-out point was considered to be that at which the pipe-to-soil potential reached the figure of −0·7 V. Similarly the third generator could be located to the east of the first. Usually, a certain amount of experimentation was necessary in order to determine the precise positions of the three generators which would give a pipe-to-soil potential graph with maximum values of 3 V and minimum intermediate values of −0·85 V. When this condition had been satisfied all three generators would be run simultaneously, and after allowing a period for polarization, a complete set of potentials would be taken together with the applied voltage and currents at the individual ground beds. At each unit the currents flowing in the pipe to east and west were ascertained by taking volt drops over 100-foot lengths of pipe. Pipelines are, of course, conductors of large cross-section and low resistance. The only means available to us of ascertaining the resistance of the pipeline is that of calculation from an assumed figure for specific resistance and pipe dimensions. The agreement obtained between current readings is not always very good, and this perhaps is partly due to variations in the pipe steel cross-section or the effect of welds. In addition, the current flowing on to the pipe in the section actually under test is often considerable.

The results of the current survey on the twin 12-in and 16-in south lines for the 270-mile section between K3 and H4 is shown in Fig. 6. The results obtained from the whole survey formed the basis of the cathodic-protection scheme described in the following paragraphs.

Design of Cathodic Protection System.

In designing a system of cathodic protection for the Iraq pipelines, it was necessary to consider not only the existing lines but also those proposed to be built in the near future. Insofar as the north line between K1 and Tripoli was concerned, it appeared that the dominant factor in determining the position of installations would not be the spread obtainable from each unit but rather the current throughput which a ground bed could be expected to cope with over a long period. The drying out of ground beds with

consequent rise in resistance is an inescapable feature of such installations in desert country. During the winter season a few violent rain storms may usually be expected in the Syrian Desert. If the ground beds have been well sited heavy rain will result in flooding of the surface. The consequent lowering of the resistance of the soil and sub-soil has a marked effect in reducing the overall resistance of an installation. At a constant applied voltage throughput may rise to twice the summer value. Following flooding, surface water usually disappears within a day or two, when the initial low resistance of the installation rises, at first sharply, and then more slowly over a period of months, as excess moisture dries out of the soil. There is no doubt that a large part of the overall volt drop between an anode and the pipeline resides in the envelope of soil immediately surrounding the ground bed. This is evident from a consideration of the manner in which current flows through the earth. In our case an additional complication is the presence of rock a few feet below the surface. The resistance of most sedimentary rocks is, of course, very much greater than the figures of 3000 to 10,000 ohms noted in these desert soils. The behaviour of ground beds after flooding is a confirmation that the principal portion of the conducting path through the ground in this type of country is the thin layer of soil overlying the bed rock. It follows from a consideration of the characteristics of these ground beds that artificial watering should have a notable effect in reducing resistance, despite the fact that only the soil in the immediate vicinity of the anode can be affected by this means. The artificial watering of ground beds is beneficial and a necessity in many locations in the desert, notwithstanding that water must be hauled by tank wagon, sometimes for long distances.

It is evident that the problem of ground-bed resistance becomes increasingly acute as currents are increased. In wet conditions very heavy currents are practicable. The author is acquainted with an installation in the Persian Gulf area in which a current of 500 amps is passed through a single mass of scrap iron to protect a few miles of bare lines laid in the sea. In our case all available evidence indicated that 50 amps might be considered as the maximum current which a ground bed in the desert could be expected to sustain over a long period having regard to the arid nature of the ground and the slight rainfall. Consideration of the heavy currents required on the northern section of the company's system led us to the conclusion that the maximum allowable current throughput would be the controlling factor in designing an installation rather than the current spread. It appeared that a greater number of small units would be required rather than a few installations each with a heavy current output.

The scheme finally adopted by the company comprises two separate and different systems of cathodic protection. This division corresponds with the differing requirements of the north and south lines to Tripoli and Haifa respectively. At the present time each of these alignments carries a twin system of 12- and 16-in pipelines. In either case the 12-in system has been in existence for some 15 years, whilst the construction of a parallel 16-in line is nearing completion on both the north and south lines. It is anticipated that further additional pipelines will be laid on the northern route during the course of the next few years. It appears as a result that the provision necessary for current requirements of the northern system mile

for mile much exceed those of the southern route. Accordingly on the Kirkuk–Tripoli line the scheme adopted calls for frequent installations each fed by a rectifier unit. These rectifiers will draw power through a transformer from an overhead high-tension line capable of supplying protective current to the entire length of right-of-way between K1 and the Mediterranean coast, a distance of 560 miles.

A diagrammatic representation of this scheme is shown in Fig. 15. From this diagram it will be seen that D.C. is supplied to the ground bed by a rectifier with a rated output of 50 V, 40 amps. The current-density requirements of the system involve the erection of a transformer–rectifier unit at intervals varying between 5 and 10 miles. The high-tension line transmits power at 11,000 V, and at each of the tapping points the transmission voltage is broken down by a 5 kVA transformer, which in turn delivers 230 V A.C. to the rectifier unit. The high-tension line is supplied from the nearest pump-station in most instances. It is evident that it is not necessary to carry the transmission line over the entire distance between adjacent supply points. Dependent on the rectifier spacing a gap may be left between the respective high-tension lines from east and west. In this manner a total distance of 45 miles of transmission line was eliminated from the overall length of the right-of-way.

The rectifier unit adopted is an oil-immersed selenium type specially designed for the purpose by the Westinghouse Brake and Signal Co. Each rectifier incorporates in the casing a transformer taking 230 V A.C. and delivering a controlled voltage to the rectifier itself. The output characteristics of the rectifier circuit are important, owing to the fact that these units operate in isolated areas and are visited only at infrequent intervals. During the winter season heavy rain will, of course, have a notable effect, amounting perhaps to 50 per cent, on the resistance of the ground bed. On the other hand, the amount of additional current required by the pipeline does not usually exceed 25 per cent between wet and dry conditions. If the rectifiers were capable of maintaining a constant voltage, then evidently the current could rise above the rated output in the event of a sharp decline of the circuit resistance with consequent overloading of the rectifier. The type of rectifier adopted guards against this contingency being designed to give an almost constant current output irrespective of the output voltage. This means that once set to a particular current output the setting is closely maintained irrespective of changes in the resistance of the external circuit. Fig. 16 shows the output characteristics of the rectifier in question. Each rectifier is provided with a voltmeter and ammeter, and adjustment is effected by simply turning a knob. The units are shaded against the direct rays of the sun and provided with adequate cooling capacity. Oil-immersed units were preferred to the air-cooled type on account of the impossibility of excluding dust and insects from the latter. Moreover, the mass of oil affords additional protection against excessive temperature rise during the heat of the day.

The rectifier output is carried to the ground bed by means of a 0·1-sq.-in. stranded bare copper cable carried on steel poles. The distance between the ground bed and the pipe is governed by local considerations of soil resistance, etc., but is seldom more than 700 yd. Naturally, the nearest suitable site to the right-of-way is selected.

The current requirements of the south leg of the system from K3 to Haifa are decidedly smaller than those of the north reflecting the smaller area of pipe surface per mile requiring protection. The pipe coating in all areas is in quite fair condition for the most part, and a wide spread of current is obtainable from a single installation. In these circumstances it appeared that the comprehensive but relatively very expensive system described above would be unnecessary and that a fewer number of isolated units would suffice to provide adequate protection. Accordingly, the finally adopted protection scheme for this section is based on isolated unattended diesel generator sets at intermediate points combined with rectifier units at the pump stations. The section in question comprises 470 miles of country between K3 (mile 150) and Haifa (mile 620), corrosion in the main has been confined to the desert areas east of Mafraq (mile 540). Mafraq lies on the Hedjaz Railway somewhat to the east of the cultivated highlands of Transjordan. The remaining 80 miles of right-of-way between Mafraq and

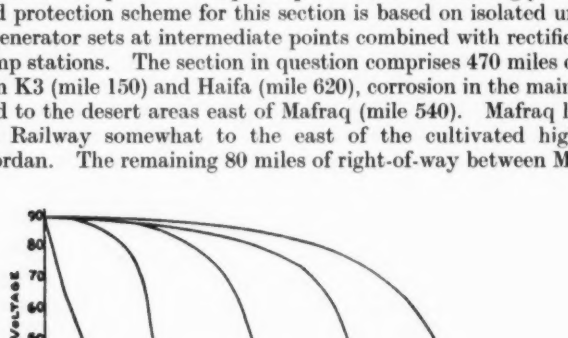


FIG. 16.

RECTIFIER OUTPUT CHARACTERISTIC.

Haifa runs for the most part over the fertile hill country of Transjordan and Palestine. Here it is only in certain isolated marshy areas in the coastal plain of Palestine that corrosion has been troublesome. These latter areas are essentially different in character from the corrosive desert, insomuch as the ground comprises a deep clay which retains moisture and shows a low resistance throughout the year. These local corrosive areas are quite suitable for the application of galvanic anodes, and magnesium has given good results hereabouts.

Reverting to the 390 miles of desert country lying between K3 and Mafraq, the picture is quite different. Here, as indeed throughout the desert, corrosion is not confined to readily identifiable localities. Taking it mile by mile, by far the greater part of this area is actively corrosive. Between K3 and Mafraq lie the five pump-stations, H1, H2, H3, H4, and H5. At each of these rectifiers are to be installed from which protection can be extended on either side of the pump-station to a distance of 10 or 15 miles. At intermediate points in the desert protection will be provided by means of fourteen isolated diesel generator sets. These sets are designed to run

unattended save for the visit of an inspector every third or fourth day. Such a system involves specially adapted units. The 12-h.p. diesel engines are provided with sufficient fuel, water, and lubricating-oil capacity to ensure continuous operation. Safety devices to shut down the units in the event of excessive temperature rises in the cooling systems are provided. An essential feature of the arrangement is that the engine is intended not to be run at more than 60 per cent of its rated output, and in normal operating conditions will be running at approximately one third of its rated capacity. The generators are designed to give a constant current output over a wide range of external resistance. This feature is necessary, as with the rectifiers, in order to avoid excessive currents as result of rain reducing ground-bed resistance. Constant current output is obtained by the use of twin generators. The first is a constant-voltage machine intended primarily to provide exciting current for the field winding of the main generator. This exciter is also large enough to provide an additional electrical load to bring the engine load above 3 h.p. when the required external output is less than this figure. The field winding of the main generator is in series with a rheostat so that the excitation current may be controlled at will similarly to the rectifier units. The connexion to the ground bed is carried by a short length of pole line.

At the pump-stations the rectifier units take A.C. power direct from the station supply at 230 V, no high-tension transformer being required. The rectifier output serves to protect both the main lines in the vicinity of the station and the internal station-service lines.

The scheme outlined in the preceding pages is being applied in the main to lines which are either new or which have been reconditioned recently. The frequency of leaks on these lines at the present time is therefore relatively slight. The intention behind the scheme is to obviate corrosion for the future. In these circumstances it is not to be expected that a striking cessation of leaks will follow the application of cathodic protection, since a new or reconditioned line rarely develops serious leaks in the first five years of its life. It will be a considerable number of years before the efficacy of the system can be demonstrated by the continued absence of corrosion leaks.

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